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THESIS

GPS EPHEMERIS MESSAGE BROADCAST SIMULATION

by

Nathan J. Browne
James J. Light

September 2005

Thesis Advisor:	Dan C. Boger
Second Reader:	Alan A. Ross

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The warfighter constantly needs increased accuracy from GPS and a means to increasing this accuracy to the decimeter level is a broadcast ephemeris message containing GPS satellite orbit and clock corrections. The ephemeris message is produced at the GPS MCS (Master Control Station) which receives GPS signal data from NGA and Air Force worldwide and uses sophisticated software to produce the orbit and clock corrections.

The problem is getting the ephemeris message to the tactical user in a forward operating area. This thesis proposed a notional architecture for pushing the ephemeris message to the tactical user. It then modeled the architecture and simulated the broadcast of the ephemeris message to a tactical user using NETWARS. The baseline architecture was simulated and analyzed and then additional constraints were placed upon the network to simulate a real-world model. The simulation results demonstrated that the architecture was feasible for ephemeris message broadcast with the constraints on time intervals between broadcasts, residual traffic and message size.

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GPS EPHEMERIS MESSAGE BROADCAST SIMULATION

Nathan J. Browne
Ensign, United States Naval Reserve
B.S., United States Naval Academy 2004

James J. Light
ENS, United States Naval Reserve
B.S., United States Naval Academy 2004

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Author: ENS Nathan J. Browne, USNR

ENS James J. Light, USNR

Approved by: Dr. Dan C. Boger
Thesis Advisor

Dr. Alan A. Ross
Second Reader

Dr. Dan C. Boger
Chairman, Department of Information Sciences

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ABSTRACT

The warfighter constantly needs increased accuracy from Global Positioning System (GPS) and one means to increasing its accuracy to the decimeter level is a broadcast ephemeris message containing GPS satellite orbit and clock corrections. The ephemeris message is produced at the GPS MCS (Master Control Station) which receives GPS signal data from National Geospatial-Intelligence Agency (NGA) and Air Force tracking sites worldwide and uses sophisticated software to produce the orbit and clock corrections.

The problem is getting the ephemeris message to the tactical user in a forward operating area. This thesis proposes a notional architecture for pushing the ephemeris message to the tactical user. It then models the architecture and simulates the broadcast of the ephemeris message to a tactical user using NETWARS. The baseline architecture is analyzed and then additional constraints are placed upon the network to simulate a real-world model. The simulation results demonstrate that the architecture is feasible for ephemeris message broadcast with the constraints on time intervals between broadcasts, residual traffic, and message size.

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I. INTRODUCTION

A. BACKGROUND

The Global Positioning System is a technology that allows users to determine their position accurately anywhere in the world. The system was originally designed for use by the United States Department of Defense (DoD) but has since expanded to commercial and individual users as well. Despite its wide variety of uses for these commercial users, GPS is still an extremely important technology for the military. GPS is used by the United States Armed Forces for navigation, tracking, bomb and missile guidance, rescue, and map updating. This thesis focuses on the bomb and missile guidance capacity of GPS.

The bomb and missile guidance capability of GPS is currently employed on the JDAM (Joint Direct Attack Munition) and the JSOW (Joint Stand-Off Weapon). These weapons can be launched from tactical aircraft platforms of the United States Navy, Air Force and Marine Corps including the F/A-18, F-16, F-15, B-1, B-2, and B-52. While the current accuracy of these weapons is excellent, it is possible for even greater accuracy and precision through the use of GPS Point Positioning.[1] GPS Point Positioning has been shown to provide real-time decimeter level GPS accuracy. GPS Point Positioning is a type of differential GPS positioning that requires corrections for the GPS satellite orbit and satellite clock errors. The combination of the satellite orbit and satellite clock corrections with the original GPS signal at a passive receiver allows for GPS Point Positioning.

B. STATEMENT OF PROBLEM

The current problem with GPS Point Positioning is providing the Zero Age of Data (ZAOD), which contains the corrections to the GPS satellite orbits and satellite clocks errors, known collectively as the *ephemeris message*, to tactical aircraft. The GPS constellation is updated on average 1.2 times per day with current ephemeris data even though the corrections are generated every 15 minutes by OMNIS, a ground-based

[1] The Air Force TENCAP project Talon NAMATH and the Navy TENCAP project Radiant ZEPHYR V both discuss the use of GPS Point Positioning.

computer system located at Schriever Air Force Base, Colorado Springs, Colorado.[2] This thesis proposes to examine the ability to deliver ephemeris data from Schriever AFB to tactical aircraft in a forward operating area using currently available terrestrial communication systems.

The communications architecture is designed to push the ephemeris data over a terrestrial IP network such as JRES/NIPRNET/SIPRNET to a Global Broadcast System (GBS) uplink site. The GBS uplink will push the ephemeris data over the GBS pipe to a GBS downlink. This GBS downlink could be to a United States Navy aircraft carrier (CVN) or a United States Air Force Air Operations Ceneter (AOC) or a Combined Air Operations Center (CAOC). The CVN, AOC or CAOC will then use the Link 16 tactical data network to forward the ephemeris data to an E-2C or AWACS command aircraft. The command aircraft will then forward the ephemeris data via Link 16 to tactical aircraft in flight. This ephemeris data will be inputted into the tactical aircraft's GPS receiver allowing for GPS Point Positioning.

This thesis will simulate the ephemeris data being pushed over the above proposed communications architecture and examine the feasibility and compatibility of this technique. Feasibility defines whether or not the communications architecture can support the size and frequency of the ephemeris message. Compatibility defines whether or not the ephemeris data moves seamlessly between the communication systems employed in the architecture.

C. METHODOLOGY

The data for this thesis is obtained using the NETWARS Simulation Program. The data for this project is collected using a progressively constructed simulation that first establishes the baseline architecture and runs a simulation of bits (the GPS ephemeris message) through the communications network simulation that has been designed. The simulation of bits is checked to ensure that it makes it through the network to the receiver and does not overload the system.

After establishing a baseline, the simulation is run multiple times using different timing for the ephemeris message, different message breakdowns and different loads

[2] Air Force TENCAP Talon NAMATH Briefing, 21 April 2005.

placed on the rest of the network. The timing for the ephemeris messages is increased to see the limit of how often the receiver can actually be updated. The ephemeris message is also broken down into the GPS satellite clock updates and the GPS satellite orbit updates with the orbital updates sent every 15 minutes and the clock updates sent at faster rates through the network. The clock updates are more essential to the receiver in order to achieve decimeter level accuracy than the orbit updates. Finally, increased loads are placed on the rest of the network to simulate other users.

The methodology for the technical side to check for the compatibility of the GPS ephemeris message through the proposed architecture will be established via research into the current systems and how they handle message traffic. This will include investigation into the data transfer at the CVN/CAOC node between GBS and Link 16, and at the tactical aircraft node between Link 16 and the GPS receiver. Link 16 will also be investigated to check for compatibility between the TADIL-J format of Link 16 and the ICD-153C format of the GPS ephemeris message.

D. ORGANIZATION OF THE THESIS

This thesis is organized as follows, Chapter II: Technologies; Chapter III: GPS Ephemeris Message Broadcast Architecture; Chapter IV: GPS Broadcast Simulation Using NETWARS; Chapter V: GPS ephemeris message architecture Simulation with shorter Time Intervals; Chapter VI: GPS ephemeris message architecture Simulation with Background traffic; Chapter VII: GPS ephemeris message architecture Simulation Varying the number and Size of the ephemeris message and Chapter VIII: Conclusion.

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II. TECHNOLOGIES

A. GPS

1. Basics

The Global Positioning System (GPS), known as NAVSTAR by the U.S. Department of Defense, is a space-based navigation system. The current system is made up of a network of 28 satellites, 24 operational and 4 backups, orbiting the earth at an altitude of approximately 12,000 miles. At this altitude, each satellite completes two full orbits in slightly less than 24 hours. The GPS system uses satellite signal time-of-arrival calculations to determine position and time for the user.

Figure 1. GPS Satellite Constellation (From: Garmin, 2005)

GPS is a dual-use system developed by the Department of Defense that is designed to support both military and civilian users. The two main services that GPS provides are the Precise Positioning Service (PPS) and Standard Positioning Service

(SPS). PPS is the full-accuracy GPS positioning service with a design specification accuracy of approximately 15 meters intended for military users. SPS is the partial-accuracy GPS positioning service and was intended to provide civilian users with GPS capability, but with minimum accuracies of 100 meters. The difference between the two GPS signals is achieved through the use of Selective Availability (SA), which is essentially an intentional degradation of the satellite signal for civilian users. The rationale behind SA was that civilian users could achieve the benefits of GPS but not at the cost of U.S. national security. The use of SA was discontinued by May 1, 2000 by order of the President of the United States although the U.S. reserves the right to turn it back on at anytime in the future when our interests may be threatened. The discontinuation of SA means that all GPS users have access to PPS.

The current types of GPS satellites in orbit, Blocks IIA and IIR, transmit two lower power signals in the microwave part of the radio spectrum that are designated L1 and L2. Civilian GPS receivers access the Coarse Acquisition (C/A) code transmitted on the L1 frequency (1575.42 MHz). Military receivers use the encrypted P-code (precise or precision code) which is transmitted on both L1 and L2 frequencies (1228.60 MHz). In the future the GPS constellation will add new signals beginning with a new C/A code transmitted on the L2 frequency. This signal will be available beginning with the initial GPS Block IIR-M satellites scheduled for launch later this year.[3] Another new signal, known as L5 and transmitted at 1176.45 MHz, will be available on GPS Block IIF satellite scheduled for launch beginning in 2007.[4] The L5 signal falls in a band which is protected worldwide of aeronautical radio navigation, and therefore will be protected for safety-of-life applications.[5]

Figure 2 outlines the GPS frequencies and signals:

[3] Davidson, Joe, *Air Force Space Command Continues GPS Modernization*, Space Daily, August 22, 2005. Available [www.spacedaily.com/news/gps-05zzzt.html], September 26, 2005.

[4] Global Security.org, *GPS III/GPS Block III* not dated [http://www.globalsecurity.org/space/systems/gps_3.htm], September 26, 2005.

[5] FAA, *GPS Basics*, [http://gps.faa.gov/gpsbasics/GPSmodernization-text.htm], June 15, 2005.

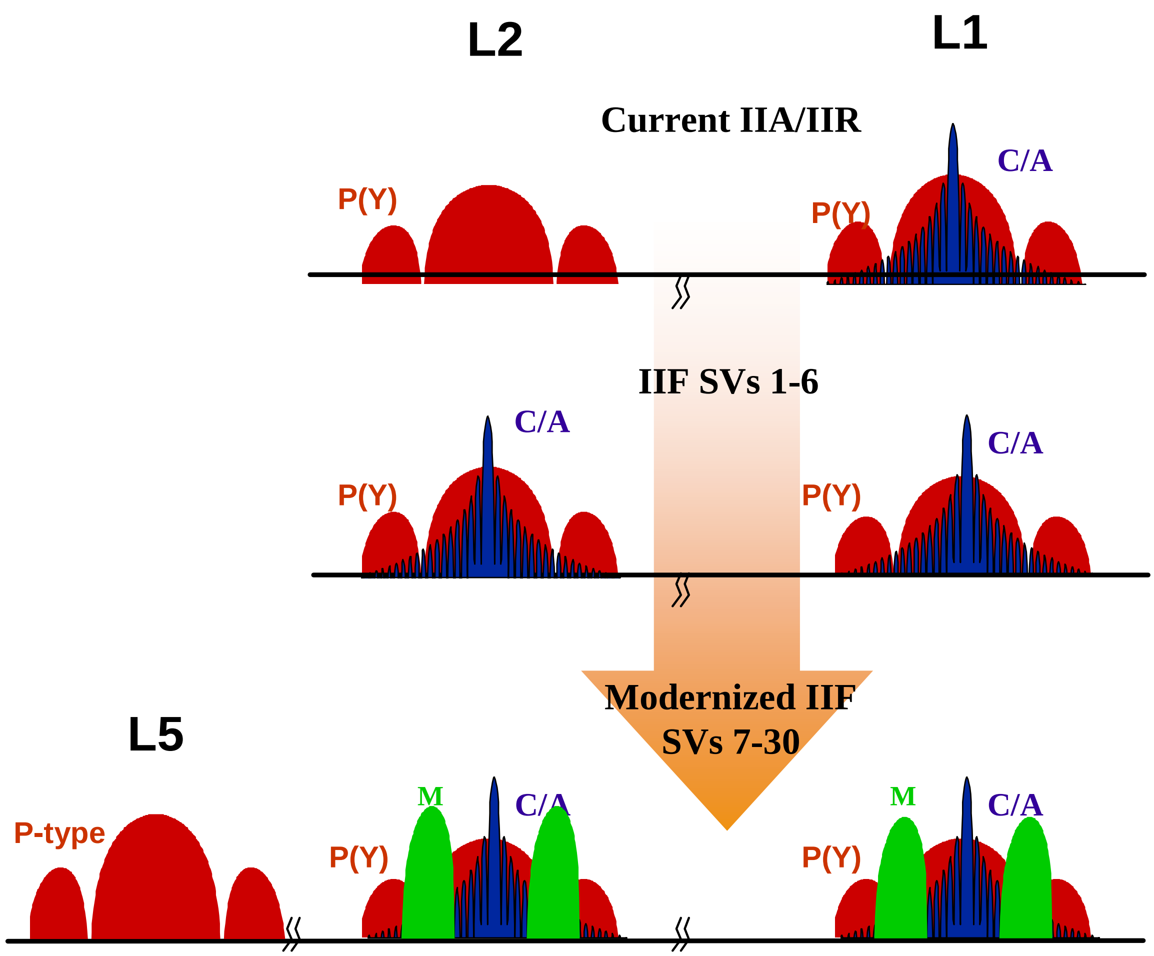

Figure 2. GPS Frequencies and Signals (From: SS3011, Lesson 22A)

2. Segments

The GPS system includes three main segments: the space segment, the control segment and the user segment. The space segment currently consists of 28 satellites in six orbital planes separated by 60 degrees and at a 55 degree inclination angle from the equatorial plane. The orbit period is 11 hours 58 minutes and its radius is approximately 26,600 km (Kaplan, 1996). The orbital design ensures that at least four satellites are always visible from any location.

The control segment of the Global Positioning System, known as the Operational Control Segment (OCS), consists of a Master Control Station (MCS), monitor stations

and ground control stations. The main operational tasks of the OCS are: tracking for the orbit and clock determination and prediction, time synchronization of the satellites, and upload of the data message to the satellites.[6] The MCS is located at Schriever Air Force Base, Colorado Springs, Colorado. The MCS receives data from the monitor stations and calculates the satellite orbit and clock corrections using a Kalman filter. These results are then passed through the ground control stations to be uploaded to the GPS satellites.

The five GPS monitor stations are located at Hawaii, Colorado Springs, Ascension Island in the South Atlantic Ocean, Diego Garcia in the Indian Ocean and Kwajalein in the North Pacific Ocean. The main operational task of the monitor stations is to continuously track all GPS satellites in view and measure the pseudoranges every 1.5 seconds. These measurements allow the monitor stations to determine the errors associated with ionospheric delay of the satellite signals. The pseudoranges are smoothed to produce 15-minute interval data which is transmitted to the MCS.[7]

The three GPS ground control stations are co-located with the monitoring stations at Ascension Island, Kwajalein, and Diego Garcia. The satellite orbit and clock corrections, previously calculated at the MCS and received by the ground control stations via communications links, are uploaded to each satellite via S-band radio links.[8] The upload takes place approximately 1.2 times per day.[9]

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[6] Hofmann Wellenhoff, 18.

[7] Hofmann Wellenhoff, 19.

[8] Hofmman Wellenhoff, 20.

[9] Air Force TENCAP Talon NAMATH, April 2005.

Figure 3. GPS OCS (From: Garmin, 2005)

The user segment of GPS consists of the receivers and antennas that process GPS signals to determine user position, velocity and time. There are four basic types of GPS receivers: (1) C/A-code pseudorange, (2) C/A-code carrier phase, (3) P-code carrier phase and (4) Y-code carrier phase measuring instruments. C/A-code pseudorange receivers measure only code pseudoranges using the C/A-code. C/A-code carrier phase receivers obtain code ranges and carrier phases from the L1 frequency. P-code carrier phase receivers are able to lock onto both the L1 and L2 frequencies. In the absence of A-S (anti-spoofing), observables are derived by first correlating the signals with a replica of the P-code. Then, after removing the P-code from the received satellite signal, phase measurements can be performed. Y-code carrier phase receivers access the P-code with A-S invoked. A-S is the ability of the GPS system to “turn off” the P-code or invoke an encrypted code as a means of denying access to the P-code to all but authorized users. The encrypted P-code is known as the Y-code. Thus, similarly to the P-code receiver code ranges and phases can be derived from the L1 and L2 frequencies by the P-code correlation technique.

3. Signals

The GPS signal carried by the L1, L2, or L5 frequency contains three different pieces of information that allow the user to determine their position with a GPS receiver. This information is the pseudorandom noise (PRN) code, ephemeris data, and almanac

data. The GPS receiver is able to identify which GPS satellite is transmitting information because the PRN acts as a unique I.D. The ephemeris data tells the GPS receiver where all GPS satellites should be at any time throughout the day. Almanac data contains information about the satellite's health and current date and time. The time component of the almanac data is essential to calculating position using GPS.

The receiver determines how far away one GPS satellite is by comparing the time the signal was transmitted by the satellite and received by the receiver. The receiver does this using the PRN code. Both the satellite and receiver generate the PRN code at the same time and since the satellite PRN code has to travel more than 11,000 miles it is delayed compared to the receiver PRN code. The amount of time that the receiver has to delay its PRN code to be in sync with the satellite PRN code is the travel time.

GPS receivers determine position by using triangulation between three or four GPS satellites. If the receiver is locked into three satellites then it obtains three distances and can provide a two-dimensional position (latitude and longitude), but this solution is problematic. The clocks on the GPS satellites and GPS receivers need to be extremely accurate because at the speed of light an error of one-one thousandth of a second equals nearly 200 miles of error in distance. GPS satellites have atomic clocks to ensure minimal timing errors but GPS receivers do not because the cost is prohibitive.[10] Thus errors in the GPS receiver clock cause inaccurate positioning when the receiver locks onto only three satellites. To ensure accurate timing at the receiver, a distance is obtained from a fourth GPS satellite. This fourth position solution leads to four spheres that do not quite intersect.[11] The GPS receiver then looks for a single time correction factor that it can subtract from all the timing measurements to cause the spheres to intersect at a single point. This correction allows the receiver to be as accurate as an

[10] The cost of an atomic clock is approximately $50,000-$100,000.

[11] The distance from any single GPS satellite lies on a sphere. Two intersecting distance spheres from two satellites forms a circle of possible user positions and three intersections yields two points, one of which is on the Earth's surface. The fourth sphere does not intersect with the other three because of clocks errors in the imprecise receiver clock. The clock errors in the receiver clock mean that the satellite and receiver clocks are not perfectly synchronized which causes the range measurements to be inaccurate. The inaccurate range measurements causes the fourth range, the one checking the other three, to not intersect with the original position.

atomic clock without having one. The receiver applies the correction to all four distances and is able to produce a more accurate three-dimensional position (latitude, longitude and altitude).

In order to compute accurate GPS solutions, it is essential to know the true position of GPS satellites. Ephemeris data describes the coordinates of GPS satellites for small portions of their orbit. Broadcast ephemeris sets are updated by the control segment every two hours and are considered valid for two hours before and after the time of ephemeris.[12] These broadcast ephemeris sets are different from *precise ephemeris data* which is obtained by utilizing a network of tracking stations and orbit processing facilities to collect and analyze satellite orbit data. Despite these continuous updates, discrepancies between the ephemeris data and the true satellite position develop over time. These differences are caused by perturbations attributed to gravitational effects of the earth and sun, magnetic forces, atmospheric drag, solar radiation effects and the earth's non-spherical shape and uneven mass distribution.[13]

4. Errors

A large number of factors contribute to errors between the receiver's true position and GPS position calculated by the receiver. This thesis focuses primarily on two types of these errors but will briefly address all types of GPS errors. GPS errors can be grouped into clock errors (satellite and receiver), orbit errors, propagation errors (ionosphere and troposphere), multi-path errors, and receiver errors. This thesis will focus on satellite clock errors and orbit errors.

Clock errors occur when the satellite or receiver clocks drift from UTC (Coordinated Universal Time). The drift from UTC means that the satellite and receiver clocks may not be synchronized, so this will affect the range measurement using the pseudorandom code. Orbit errors, also known as ephemeris errors, occur when the GPS satellite's position is not accurately reported to receiver. Ephemeris errors are caused by gravitational effects of the earth and sun, magnetic forces, atmospheric drag, solar radiation effects, and the earth's non-spherical shape and uneven mass distribution.[14]

[12] Bisnath, 2000.

[13] Kaplan, 1996.

[14] Kaplan, 1996.

These two errors, the satellite clock error and the satellite orbit error, are what the GPS ephemeris message corrects in its broadcast to the GPS receiver.

Propagation delays are caused by GPS signals propagating through the ionosphere and troposphere. In the ionosphere, the part of the atmosphere 80 to 1000 km above the earth's surface, GPS signals are affected by charged particles which delay the signal. This delay is dependent upon the frequency of the signal[15] so dual-frequency receiver can eliminate this error by comparing the relative speeds of the two GPS signals. In the troposphere, which extends from sea level to 80 km above the earth's surface, signal delays are caused by the presence of water vapor. Delays caused by water vapor can be modeled using temperature, pressure and humidity. Multipath error occurs when the GPS signal is reflected off objects such as tall buildings or large rock surfaces before it reaches the receiver. This reflection increases the travel time of the signal since it has to travel a longer distance before reaching the receiver due to the reflection.

B. GPS POINT POSITIONING

1. Differential GPS

Differential GPS (DGPS) is a way to correct the inaccuracies of the GPS systems by placing a receiver, known as the reference station, on an accurately surveyed location. The reference station then compares the theoretical distances to the observable GPS satellite with the actual measurement to the satellite according to the pseudorandom noise code. The difference between the theoretical distance and the actual measured distance to the satellite represents the pseudorange error. A GPS receiver in the same general area as the reference site can then apply the negative residual from the pseudorange errors to its own measurements to realize its true position. The assumptions are that the GPS receiver is receiving the same set of GPS satellite signals as the reference site at the same time so that the errors for both will be the same. Additionally, a one-way data link needs to be established between the reference site and the GPS receiver so that receiver obtains the pseudorange errors. In Evans et al "The Global Positioning System Geodesy Odyssey," the authors note that:

[15] The ionospheric delay is proportional to the inverse of the square of the carrier frequency.

> DGPS is fundamentally a relative positioning system. The monitor receiver could be (and sometimes is) located on a moving vehicle such as a ship, airplane or satellite. In this case, the measurement corrections supplied to the user, who is positioned relative to that vehicle, are the negative of the measurement residuals from the vehicle position computation. When multiple monitor receivers are used they, of course, must be located accurately relative to one another. The requirement for accurate surveying of the monitor receiver position arises only from the desire to transform the relative positioning accuracy into an absolute accuracy.

2. GPS Point Positioning

GPS Point Positioning is a form of DGPS without a ground-based reference site. It uses satellite and clock updates from the MCS to have decimeter level GPS accuracy. Currently, GPS Point Positioning has been performed after the fact (not in real time) by Naval Surface Warfare Center, Dahlgren Division.[16] To perform GPS Point Positioning in real time the satellite orbit and clock updates must get to the user over a data link of some sort from the processing center, and they must be nearly continuous in order to constantly account for errors in the system. Two service-specific programs are working on the problem of getting the satellite orbit and clock updates to users. These programs are Navy TENCAP (Technical Exploitation of National Capabilities) Radiant ZEPHYR V and Air Force TENCAP Talon NAMATH. Both programs propose architectures similar to the one used in this thesis for the NETWARS simulation.

3. Civilian Applications Similar to GPS Point Positioning – Starfire

A majority of the material in this section comes from Hatch et al "StarFire: A Global High Accuracy Differential GPS System."

A commercial product has emerged that provides decimeter level accuracy worldwide differential GPS. StarFire Wide Area Differential GPS System (WADGPS) was developed by NavCom Technology, Inc. and AG Management Solutions (which are both components of John Deere and Company) for agricultural applications. NavCom operates StarFire. The predecessor to the current StarFire system had continental size coverage, of which the principal source of error was the inaccuracy in the broadcast GPS orbits. In order to convert regional systems using DGPS to a global DGPS system, accurate real-time GPS orbits needed to be generated. The Jet Propulsion Laboratory

[16] Evans meeting, 2005.

(JPL) developed a technology called RTG (Real Time GYPSY) to compute the orbit and clock corrections needed for a global DGPS system for the National Aeronautics and Space Administration (NASA). Unfortunately, JPL had no means to distribute their product to isolated users. NavCom leased the software from JPL and broadcasts the correction stream over three Inmarsat satellites to provide global coverage. NavCom also contracted with JPL to receive the data from JPL/NASA reference sites in order to coordinate the NavCom reference sites. The final product, StarFire, is a global DGPS system that provides decimeter level accuracy anywhere in the world. StarFire does not require base stations, and its positioning results are absolute, not relative. This service can go beyond agricultural applications, customers in the offshore market are using StarFire, and there are abundant uses in the commercial world for accurate positioning.

The accuracy of the StarFire system is a result of the following key characteristics:

- GPS measurement data from a global network of dual frequency reference receivers

- Very accurate orbit calculations using JPL’s RTG technology

- Modeling of all significant error sources

- High quality dual frequency mobile receivers

- Highly redundant measurement data, processing structures, and communication links

There are seven major components in the StarFire system:

- Reference Network: reference receivers that continuously provide the raw GPS observables to the Hubs for processing. These observables include dual frequency code and carrier measurements, ephemeredes, and other information.

- Processing Hubs: facilities at which the GPS observables are processed into DGPS corrections. There are two geographically separated (Redondo Beach, CA, and Moline, IL), independent Hubs that operate fully in parallel, with each continually receiving all the measurement data and each computing corrections

that are sent to the uplink facilities for the satellites. The Hubs are also the control centers for StarFire, from which the system operators monitor and manage StarFire.

-Communication Links: provide reliable transport mechanisms for the GPS observables and for the computed corrections. A wide variety of links are used to ensure that data are continuously available at the Hubs and that corrections can always be provided to the Land Earth Station (LES) sites.

- Land Earth Stations: satellite uplink facilities that send the correction data received from the Hubs to the geostationary satellites.

-Geostationary Satellites: used to distribute the corrections to users via L-band broadcasts. The corrections from the LESs are broadcast on L-band frequencies to the users. Three Inmarsat geostationary satellites are used to provide correction coverage over most of the Earth (between +76 North and -76 degrees South latitude).

-Monitors: user receivers distributed throughout the world that use the broadcast corrections and provide their navigation information to the Hubs in real time.

-User Equipment: uses the broadcast corrections along with local GPS observables to produce very precise navigation. The user equipment makes dual frequency GPS observations which remove ionospheric effects and combines these with the broadcast corrections in a Kalman filter.

The current RTG StarFire system is the global system that improved upon the preceding WCT (Wide Area Correction Transform) StarFire wide area DGPS. The WCT network was installed in North America, South America, Europe, and Australia. Eight reference sites were used in the US WCT network, five in the Australian, four in the European, and three in the South American network. Each reference receiver sends information with the dual frequency observables for all of the GPS satellites tracked at the reference receivers (delivered at 1 Hz in real time), and the broadcast ephemeris records from the reference receivers (delivered in real time) to all satellites in view. Each reference receiver also sends system integrity information to the two Processing Hubs.

Using this information, the normalized pseudoranges for each satellite are combined in a weighted average to form a single, wide area pseudorange correction for that satellite. All of these corrections for the satellite in view are formatted into a tightly packed, binary message and sent from the Hub to the LES for the geostationary L-band communications satellite where they are uplinked for broadcast to users throughout each region. The WCT corrections are used as a backup to the current RTG corrections in those regions covered by WCT StarFire.

WCT StarFire uses averaging of weighted refraction corrected satellite range errors to produce corrections that are valid over large regions. This averaging degrades with distance from the area of observation. The principal source of error is inaccuracy in the GPS satellite orbits. The RTG StarFire improves upon WCT by a state approach in which the primary states that are estimated are orbit and clock errors. These are continuously computed for all the GPS satellites based on global observations. These two states are globally valid and do not depend on the user's position. The two Hubs receive raw data from JPL and NavCom's dual frequency Reference Stations every second to compute a new set of orbital corrections every minute and a new set of clock corrections every few seconds for each GPS satellite. Accurately predicting each satellite orbit is essential to precise corrections and has been verified from recorded International GPS Service records. The satellite clocks vary more rapidly and require the normalization of clock data from the reference sites, which is performed by using the clock at a specified reference site as a standard. The ionospheric error is eliminated by the use of dual frequency receivers at both the reference sites and user equipment. Fifty dual frequency reference receivers are distributed throughout the world to generate the GPS measurements that are processed at the Hubs. The precise position of each reference antenna is determined by a geodetic survey and tied to the International Terrestrial Reference Frame (which is the underlying geodetic framework for GPS, and is also tied to WGS-84). The data between Reference Stations, LESs, and Hubs is transferred via the Internet, frame relay, ISDN, VSAT, and dedicated digital circuits. All of these are used to ensure reliability through redundant communication links. Most reference sites use the internet, and due to the large number of reference sites, they provide protection from local internet problems. Frame relay is primarily used in the US

for the reference sites, as well as for the Hubs. LESs rely on the internet as well, but because their path is the most critical, the link is backed up by ISDN and VSAT. It is essential that the latency in the links be low so that the clock corrections can be computed promptly and that the distribution time to users of the computed corrections also be low, so that times are not extrapolated for very long.

The RTG StarFire system is a commercial product that is able to get decimeter level accuracy to its users. NavCom has created a robust system that tackles the primary errors in DGPS (satellite orbits and clocks) and is able to quickly distribute corrections to its users every minute. This is the exact message that the military is able to compute using OMNIS (Chapter 1.B), but as yet has been unable to deliver to the tactical user. This thesis will simulate the delivery of the message to the tactical military user.

C. GBS

1. Basics

Global Broadcast Service (GBS) was created from Operations DESERT SHIELD/STORM, the first "information war," in order to meet worldwide information dissemination requirements. This conflict exposed the limited ability of the United State's military and civilian satellite communication systems to transfer information electronically or provide responsive, high-capacity communications to deployed, mobile tactical units. The mission need statement for GBS required:

> A high capacity broadcast capability is needed to provide timely dissemination of information products, such as imagery, intelligence information, missile warning, weather, record message traffic, joint and service-unique news, education, training, video, Morale Welfare & Recreation (MWR) programming, and/or other desired information.[17]

In 1996 NRO and DoD rapidly integrated key commercial technologies to deploy the first operational use of the GBS in the peacekeeping operation in Bosnia and called it the Joint Broadcast System (JBS). GBS uses commercial direct broadcast satellite technology to provide critical information to the nation's warfighters. It is a space-based, high data rate communications link for the asymmetric flow of information from the

[17] FAS, *Global Broadcast Service* not dated. [http://www.fas.org/spp/military/program/com/gbs.htm] July 12, 2005.

United States or rear echelon locations to deployed forces. GBS can quickly disseminate information products to a variety of Joint military user platforms.

2. Segments

GBS consists of a system of transmit suites, a space segment, and receive suites. The transmit suites also serve as the control segment, and include a Satellite Broadcast Manager (SBM), a Primary Injection Point (PIP), and Theater Injection Points (TIP). The space segment consists of GBS payloads on Ultra High Frequency Follow-On (UFO) satellites. The GBS Receive Suite Broadcast Managers (RBMs) are fixed ground stations or transportable units that distribute the GBS product.

The transmit suites serve as the dissemination points for GBS information provided from national and theater sources. They integrate, encrypt and package multi-media information and provide a bit stream to the PIP for Radio Frequency (RF) transmission to the satellite.[18] Three SBMs provide the PIP for the GBS product payload onboard UFO-8, UFO-9, and UFO-10. These three facilities are located at Wahiawa, Hawaii; Norfolk, Virginia; and Sigonella, Italy. Within a theater, the Theater Information Manager (TIM) works with the GBS to build information products. These information products are collected through the Non-Classified Internet Protocol Router Network (NIPRNET), the SECRET Internet Protocol Router Network (SIPRNET), the Global Command and Control System (GCCS), and File Transfer Protocol (FTP).[19] GBS also has the capability, through use of the TIP, to inject information directly from within a theater of operations.

The space segment consists of the three GBS payloads onboard UFOs 8, 9, and 10. The GBS payload operates independently from the UFH and EHF payloads onboard the UFOs. The payload aboard each satellite is made up of two uplink antennas (one fixed and one steerable), four transponders, and three steerable downlink antennas. The downlink antennas include two spot beams that cover greater than a 500 nautical mile diameter area. The spot beams provide data broadcast up to 24 Mbps each and one 2000 nm wide-area spot beam which provides a data broadcast stream of 1.54 Mbps. The GBS payload serves as a "bent pipe" for the data transmission. Uplink signals are received,

[18] Raytheon [http://www.raytheon.com/products/gbs]

[19] Wheeler, 7-8.

converted to a downlink frequency, switched to a downlink transponder, and re-transmitted via a spot beam. There is no demodulation or signal processing done on board the satellite.[20]

The Receive Suite, based on a small 18-inch satellite antenna, will receive and convert the RF downlink signal into a bit stream for receive broadcast management decryption and distribution to end users. There are six different receive suite configurations (fixed ground, transportable ground, shipboard, sub-surface, airborne, and man portable) that allow for both a land and sea-based capability to receive the GBS broadcast. Each of the receive suites include a Receive Terminal, Cryptographic Equipment, and a Receive Broadcast Manager. Each suite is capable of receiving one broadcast stream, operating as a stand-alone unit or Local Area Network connection, and operating unattended once installed.[21]

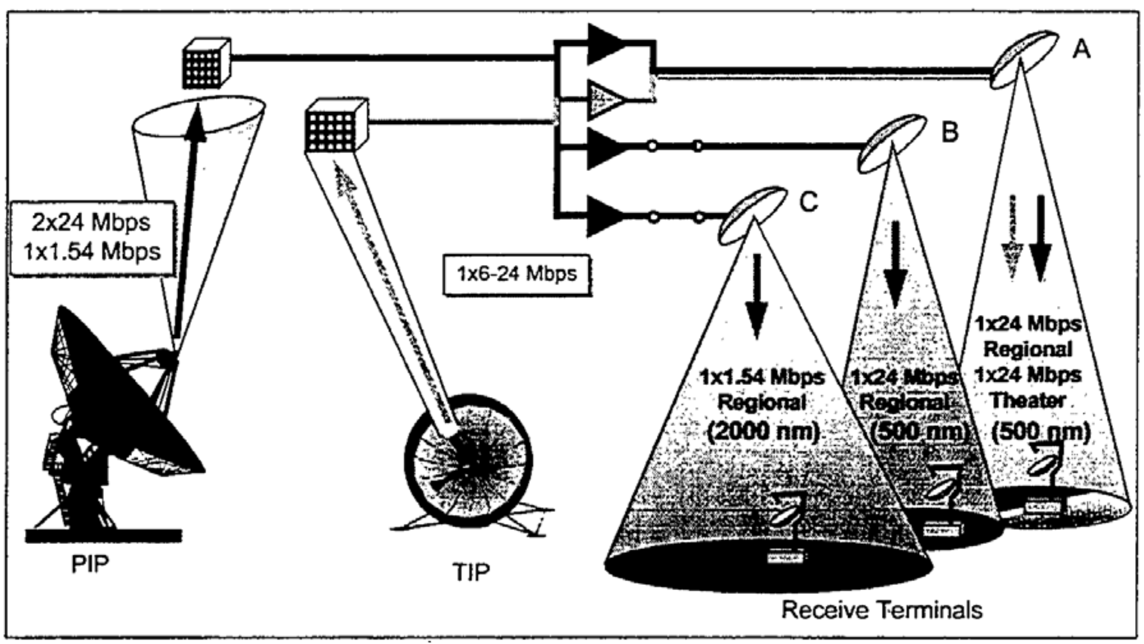

Figure 4. GBS Architecture (From: Headquarters, December 1998).

[20] Boeing, *UHF Follow-On Global Broadcast Service* not dated [http://www.boeing.com/defense-space/space/bss/factsheets/601/gbs/gbs/html] July 12, 2005.

[21] Wheeler, 9-10.

The broadcast is conducted under the support of the GBS Program Office and is implemented by the NRO Operational Support Office (OSO) and the Defense Information Systems Agency (DISA). GBS is an extension of the Defense Information Systems Network (DISN) and a part of the overall DoD MILSATCOM Architecture.[22] It has an open architecture which can accept a variety of input formats. It exploits commercial off-the-shelf (COTS) technology. It will interface with, and augment, other major DoD information systems, as well as other theater information management systems.

GBS is being implemented in three phases. Phase I, completed in FY01, consisted of leased commercial satellite services and commercial off-the-shelf Receive Suites. Phase II, which will be completed in FY08, consists of a transponder package hosted on Ultra-high Frequency Follow-On Satellites 8, 9 and 10. Phase III, FY08-15, will be defined as part of future SATCOM architecture.[23]

D. LINK 16

1. Basics

JTIDS (Joint Tactical Information Distribution System) is the communications component for Link 16. Link 16 is an encrypted, jam-resistant, nodeless tactical digital data link network. The purpose of tactical data links is to exchange real-time information allowing fast-moving participants to maintain situation awareness in the modern battle field. In theory Link 16 could be employed by all types of platforms both air and ground but it is primarily used by aircraft to exchange real-time information with each other and supporting ground units. As every fighter pilot knows, the major factor in determining the outcome of any modern air-to-air engagement is not the agility of his aircraft or the range of his weapons; it is his ability to acquire and maintain better situational awareness than his opponents throughout combat and Link 16 provides this capability. Situation Awareness refers to the pilot’s ability to maintain a `mental air picture', including the positions and vectors of all participants, both friendly and bogeys.

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[22] FAS [http://www.fas.org/spp/military/program/com.gbs.htm]

[23] Global Broadcast Service Joint Program [http://www.losangeles.af.mil/SMC/MC/gbs.htm]

Link 16 terminals implement the Tactical Digital information Link-J (TADIL-J) message standard. This architecture provides a common communications net to a large number of airborne and surface elements within line-of-sight. By using one or more members of the net as relays, the net can be extended to platforms beyond line-of-sight. Any terminal can be employed as a relay.

The precursor tactical data links to Link 16 were Link 4 and Link 11. Link 4 and Link 11 are still used today and although Link 16 represents an improvement on these Links, it will not replace them but rather be a preferable alternative when feasible.[24] Link 4 is a non-secure data link used for providing vector commands to fighters. There are two variants: Link 4A and Link 4C. Link 4A is a fighter-to-controller data link that uses the principle of Time Division Multiplexing (TDM) to derive apparently simultaneous channels from a given frequency spectrum. It connects two points by assigning a sequence of discrete time intervals to each of the individual channels. Thus, one controller can control multiple aircraft independently on the same frequency. Link 4C is a fighter-to-fighter data link which is intended to complement Link 4A, although the two links do not communicate directly with each other. Link 11 is a medium-speed, NATO-standard, HF/UHF tactical data information link. Link 11 is based on 1960s technology and is therefore a relatively slow link that normally operates on a polling system, with a Net Control Station (NCS) polling each participant in turn for their data. If the NCS goes down then the link is no longer operational.

The Link 16 program began in 1975 and the Joint Operational Requirements were established in March 1976. Two separate JTIDS programs were started in the early 1980's; one in January 1981 when the Army and Air Force were authorized to proceed into Full Scale Development (FSD) with the Air Force as the lead service and another in January 1982 when the Navy and Marine Corps were authorized to proceed into FSD with the Navy as lead service. In FY86 the SECDEF redirected the Navy JTIDS program and terminated the development of JTIDS phase II, directing the Navy and Marine Corps to use the Air Force FSD equipment modules. In June 1991, the Navy received approval to procure Low Rate Initial Production Class 2 and 2H terminals. After completion of

[24] Jane's Online, *Digital Datalinks.*

various multi-service and multi-platform tests the Navy proceeded to Full Rate Production in March 1995. The first successful employment of Link 16 shipboard and aircraft terminals occurred when the USS Carl Vinson (CVN-70) Battle Group deployed to the Western Pacific in early 1994.

Link 16 was developed to replace the older tactical data links. It contains a number of improvements over the older links which are displayed in the following Table 1:

	LINK-16	LINK-11	LINK-4A	LINK-4C
Surveillance/WC	YES	YES	NO	NO
Air Control	YES	NO	YES	NO
Fighter-to-Fighter	YES	NO	NO	YES
Secure Data	YES	YES	NO	NO
Extended LOS	YES (Relay)	YES (HF)	NO	NO
Secure Voice	YES (2 Channels)	NO	NO	NO
Jam Resistant	YES	NO	NO	NO
Positive ID	YES	LIMITED	LIMITED	LIMITED
Navigation	YES	NO	NO	NO
Data Forwarding	YES	NO	NO	NO
Flexible Net	YES	NO	NO	NO

Table 1. Tactical Data Link Comparison (From: Jane's Online, 2005)

2. Functions

The functions currently supported by Link 16 include: Net Entry (synchronization), Relative Navigation (navigation and grid lock), Blue Force Reporting (identification), Mission Management and Weapons Control (MM/WC) (force orders), Surveillance, Air Control, Secure Voice, and Electronic Warfare (EW). Link 16 categorizes these functions into communities of interest or Network Participation Groups (NPGs).

Data on Link 16 can be grouped into NPGs which enables networks to be planned so that the transmission and reception of data can be selectively managed. In the older data links such as Link 11, all participants in the network received all the data that was

transmitted regardless of whether it was relevant to their role or information requirements. The use of NPGs means that the source does not need to know who the recipient will be, and only the users that need the data will have access to that NPG and will receive all associated messages.[25] The NPGs listed below in Table 2 may or may not be included in a given network, depending on the objectives and functional requirements that the network was designed to fulfill.

NPG	Function
1	Initial Entry
2	RTT A
3	RTT B
4	Network Management
5	PPLI A
6	PPLI B
7	Surveillance
8	Mission Management
9	Air Control
10	Electronic Warfare
12	Voice A
13	Voice B
14	Indirect PPLI
18	Weapons Coordination
19	Fighter-to-Fighter
27	PPLI (JOINT)
28	Distributed Network Management
29	Residual Message
30	IJMS Position and Status
31	IJMS Message

Table 2. Network Participation Groups (From: Jane's Online, 2005)

The Net Entry (Synchronization) Function of JTIDS works to ensure that each participating JTIDS terminal acquires and maintains an accurate knowledge of system time. A single designated unit, the Network Time Reference (NTR), establishes the system time. Once operating, the NTR unit begins broadcasting transmission of the

[25] *TADIL J*, FM 6-24.8, page I-3.

system time and net entry message. Other terminals enter the network when operators enter a best estimate of system time (UTC), and then the terminals "looks for" the net entry message. Once a message is received, the entering unit starts transmitting round trip timing (RTT) messages in order to refine its estimate of system time. When the unit's time is properly refined, "fine sync" is declared and full link participation is possible.

The identification function of Link 16 is performed through the transmission of PPLI (Precise Position, Location and Identification) messages. These messages are transmitted periodically by each member of the Link 16 network. The Status portion of the Identification function includes enough information to eliminate the need for voice status updates.

In Link 16, Surveillance is the exchange of track and track management messages. The Air Control function of Link 16 is similar to Link 4A. Command and Control (C2) units, including ships and E-2C Hawkeyes, exercise control over fighters, providing tracks, mission assignments, and vectors. JTIDS supports two secure voice circuits, each with 127 subcircuits. The voice to data conversion is performed in the JTIDS terminal and does not require host processing.

3. Communications Architecture

The JTIDS terminal produces the Link 16 waveform. The Link 16 JTIDS waveform uses pulsed transmission in the 960-1215 MHz (UHF) frequency band.[26] The waveform is designed to provide complete communications service to multiple users within a hostile electromagnetic environment. The waveform employs a number of techniques to insure maximum jam resistance including spread spectrum, frequency hopping, Error Detection and Correction (EDAC) coding, pulse redundancy, pseudorandom noise coding, data interleaving, automatic data packing and inherent relay.

Frequency hopping involves each radiated pulse being pseudorandomly assigned to one of the 51 authorized center frequencies. The center frequencies are spaced at 3 MHz intervals on 51 frequencies located in the 960-1215 MHz range excluding 1008-1053 MHz range and the 1065-1113 MHz range because these ranges are reserved for

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[26] *TADIL J*, FM 6-24.8, page I-3.

Identification, Friend or Foe (IFF).[27] This pseudorandom assignment of frequency is referred to as the hopping pattern. The NPG, the net number (discussed below in stacked nets), and the assigned transmission crypto variable determine the hopping pattern. This allows multiple transmitters to be within Line-of-Sight transmitting information without causing mutual interference. The frequency band that JTIDS utilizes has been designated for aeronautical radio navigation and Air Traffic Control (ATC) in the United States by the Federal Aviation Administration (FAA). Therefore all JTIDS frequency assignments are obtained with concurrence from FAA headquarters.

The Link 16 access is controlled through the Time Division Multiple Access (TDMA) protocol. TDMA apportions timeslots to each user and each user take turns transmitting or receiving based upon time. This is similar to Time Division Multiplexing with the only difference being that in Time Division Multiplexing there is one user on each end of the circuit while in TDMA a large number of network participants can access the data in the network. The basic unit of time in Link 16 is called a frame which is 12 second in length. The frame is composed of 1536 individual access/transmit units called time slots. Frames occur repeatedly as long as the link is operational. Each of the 1536 timeslots are assigned to platforms operating in the network under the function of either transmitting or receiving for that platform.[28]

Stacked nets are used on Link 16 networks to increase system throughput. Stacked nets support the voice, air control and fighter-to-fighter functions of Link 16. The selection of a particular net from a stacked net function changes the terminal’s frequency hopping pattern. The use of stacked nets allows multiple air controllers to operate independently.[29]

The survivability of the JTIDS waveform depends upon its security, jam resistance, sufficient power to provide LOS service and extended service beyond LOS through use of relay. Security is employed for the JTIDS waveform by using Message Security (MSEC) and Transmission Security (TSEC). JTIDS employment of frequency hopping as well as time hopping increases its anti-jam capability. Frequency hopping

[27] *TADIL J*, FM 6-24.8, page B-2.

[28] *TADIL J*, FM 6-24.8, page I-3.

[29] *TADIL J*, FM 6-24.8, page I-5.

forces the jammer to spread its energy over a larger bandwidth which reduces the amount of jammer energy per individual frequency while the time hopping (jitter in the modulation of the start time of message transmissions) prevents the jammer from attacking the sync part of the message with peak power.

The topology of Link 16 is a nodeless architecture which means that there is not a single unit required to maintain communications. In Link 11, the NCS is a node so if it goes down the link goes down. The closest thing in Link 16 to a node is the Net Time Reference, and after the network has been established it will continue to function for hours if the NTR goes down.

4. Equipment

The equipment of JTIDS includes the terminals themselves that produce the Link 16 waveform as well as the TADIL-J database, human machine interface controls, and displays. All the terminals in the JTIDS Class II terminal family produce an identical waveform that can be received by any other member of the family.

The terminals themselves are made up of a number of components including the digital data processor, the interface unit, the secure data unit, the receiver/transmitter, the high power amplifier (not found on all terminals) and at least two antennas. The Digital Data Processor (DDP) performs message formatting and TDMA management functions. The interface unit provides the functions necessary to adapt the DDP to the specific platform. The secure data unit is the KGV-8B which contains the cryptovariables (crypto keys) required to provide both message and transmission security. The Receiver/Transmitter (R/T) unit creates the outgoing RF stream of pulses. The High Power Amplifier boosts the power of outgoing transmissions.[30]

E. NETWARS

1. Basics

Network Warfare Simulation (NETWARS) is the Joint Chiefs of Staff standard for modeling military communications systems. It is a desktop software application that measures and assesses the information flow through tactical, operational, and strategic

[30] *TADIL J*, FM 6-24.8, page B-1.

communication networks. NETWARS has modeling and simulation capabilities that assess the information flow. It is a discrete event simulator developed using the Optimized Network Engineering Tool (OPNET) Development Kit (ODK). It is designed to analyze military communications networks through the use of reusable communications device models (CDM), military doctrine, and network traffic information in the joint arena. The primary objective of the NETWARS program is to provide an integrated ability to analyze communication networks. NETWARS also provides a validated simulation capability so that studies can be consistent throughout the Unified Combatant Commands, Services, and Joint C4I community.

NETWARS was born out of the concern that C4I systems' critical tactical information exchange processes would collapse under the unexpected effects of full operational combat network loading. In 1996, LTG Bucholz, the Director of Command, Control, Communications, and Computer Systems, J-6 (Joint Staff), raised these concerns from the C4I systems-of-systems envisioned in Joint Vision 2010 and other guidance documents. LTG Bucholz addressed his concern by initiating an effort to develop a communications modeling capability to credibly model tactical, operational, and strategic military communication demands under the stresses and inefficiencies that combat places on communication systems.

The NETWARS software allows the ability to plan, evaluate, optimize, and study military communications networks and supporting commercial networks. The following is a brief summary of how a simulation is constructed and analyzed. Within the NETWARS program, the top level view shows the Organizations to be represented in the model. Each organization has Operational Facilities (OPFACS), which are created to represent collections of communications devices. Each communication device in the program has the characteristics and attributes of the actual equipment, so the program can virtually perform each communications function accurately. The communication devices required for the models are selected from a library called the Object Pallet, and can be linked by selecting an appropriate link from the Object Pallet. Data rates, user profiles, and information traffic can be configured for each device, allowing 'loaded' traffic to be routed between hosts. Once all the devices, their characteristics, and links are defined, the simulation is run and produces statistics to be analyzed.

2. Architecture

NETWARS consists of five functional elements, which are: (1) Database Libraries; (2) Scenario Builder; (3) Capacity Planner; (4) Simulation Domain; and (5) Results Analyzer. Figure 5 is the NETWARS functional architecture:

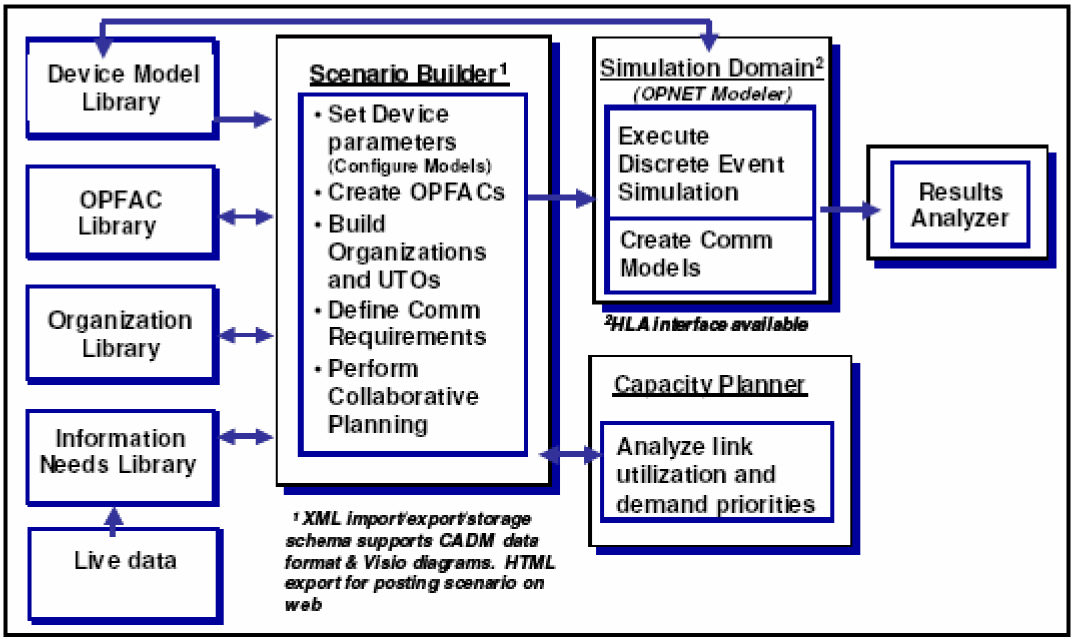

Figure 5. NETWARS Functional Architecture (From: DISA, 2005)

The Database Libraries include four primary databases: (1) Communications Device Model Library; (2) OPFACs Library; (3) Organization Library; and (4) Information Exchange Requirement (IER) Library. The simulator uses these libraries to obtain detailed information about the communications systems used during the analysis. The CDM library contains the fundamental building blocks used in NETWARS, and the models that have been developed by the Services to represent the protocols and functionality that are found in physical devices. Examples of Navy CDMs include radios, patch panels, multiplexers and tactical communications data links. The OPFAC Library is used to represent logical collections of CDMs, such as a tank or a Network Operations Center (NOC). The Organization Library is built from one or more OPFACs that are connected with various communications links. These include point-to-point, wireless, and broadcast links. Information Exchange Requirement Libraries are used to

provide the simulation with details about the traffic, such as the type (voice, video or data), the source and destination of the message, its size, and the frequency with which the message is sent.

The Scenario builder defines how the OPFACs, Organizations, links and IERs will be used during the simulation. OPFACs and Organizations can be developed, and links can be assigned. Mobility can be given to organizations to represent the real-time movement of units throughout the course of the simulation. IERs are associated with devices, and message attributes are defined here. Periods of failure and recovery of OPFACs are also specified within the Scenario Builder.

The Capacity Planner evaluates and optimizes network link capacities. The Capacity Planner evaluates a given scenario to determine the configured network's average utilization, hop count, and capacity. It can also optimize a network by using a simulated annealing algorithm that mutates the current solution to create new solutions for choosing an optimum solution. It can determine optimum link capacities and utilizations.

The Simulation Domain consists of the Simulation Engine (OPNET Modeler) and a Simulation Conversion Module. The Simulation Conversion Module translates the organizational representation and data flows into discrete events between the sender and receiver of specific communications equipment representations understood by the Simulation Engine.

The Results Analyzer allows an analyst to examine the Measures of Performance (MOPs) that are collected during a simulation. These MOPs are grouped into six categories: MOPs for a destination OPFAC; MOPs for a source OPFAC; global MOPs; device-level MOPs; MOPs for inter-OPFAC links; and MOPs for broadcast radio networks.

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III. GPS EPHEMERIS MESSAGE BROADCAST ARCHITECTURE

A. BASELINE ARCHITECTURE

The two proposed architectures for the GPS ephemeris message updates are shown in Figures 6 and 7 below. The primary difference between the proposed architectures is the difference in service specific nodes for the United States Air Force and the United States Navy, respectively. This difference is purely service specific and the communication devices involved do not in fact differ between the two architectures.

Both architectures begin at the GPS Master Control Station at Schriever AFB, Colorado Springs, Colorado. The OMNIS system at Schriever AFB generates GPS ephemeris message updates. These updates are sent over terrestrial IP networks (JRES/NIPRNET/SIPRNET) to the continental GBS uplink site. This GBS uplink site pushes the ephemeris updates over the GBS direct satellite broadcast service to a GBS downlink site in theatre. At this point the actual unit nodes of the architecture differ but the communications medium does not. The GBS downlink site is represented by either a United States Navy aircraft carrier (CVN) or a United States Air Force Combined Air Operations Center (CAOC). The CVN or the CAOC forwards the GPS ephemeris update message over the Link 16 Tactical Data Network. The nodes in this network are the CVN or CAOC broadcasting to an airborne Link 16 relay such as the United States Navy E-2C Hawkeye or the United States Air Force E-3 AWACS (Airborne Warning and Control System). The Link 16 relay aircraft forwards the ephemeris update message to the tactical aircraft in flight. The tactical aircraft incorporates the ephemeris message into its GPS receiver and ignores the ephemeris message from the GPS satellite allowing for GPS point positioning.

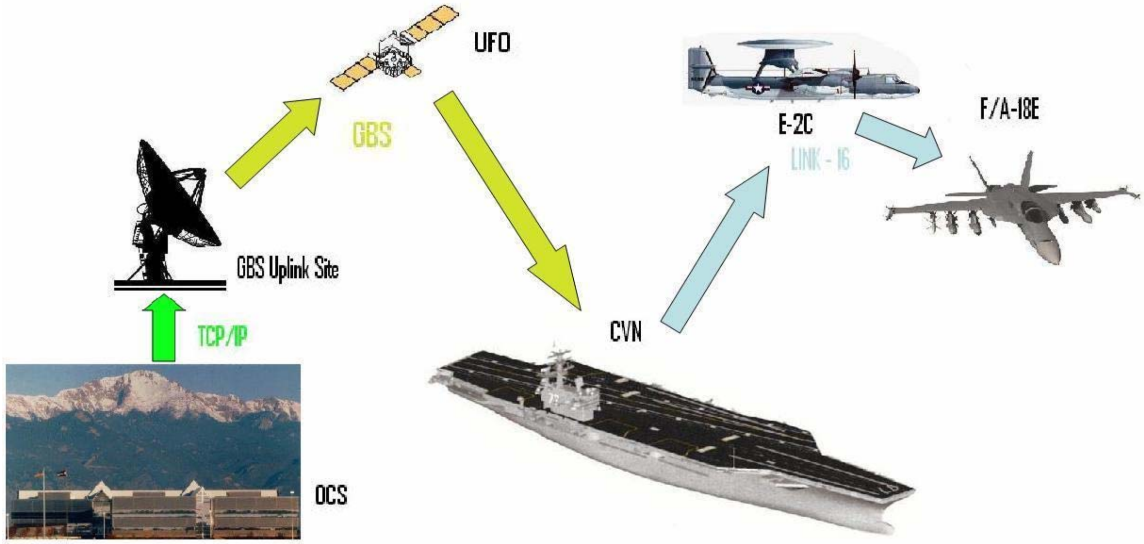

Figure 6. Navy Architecture for GPS Ephemeris Message

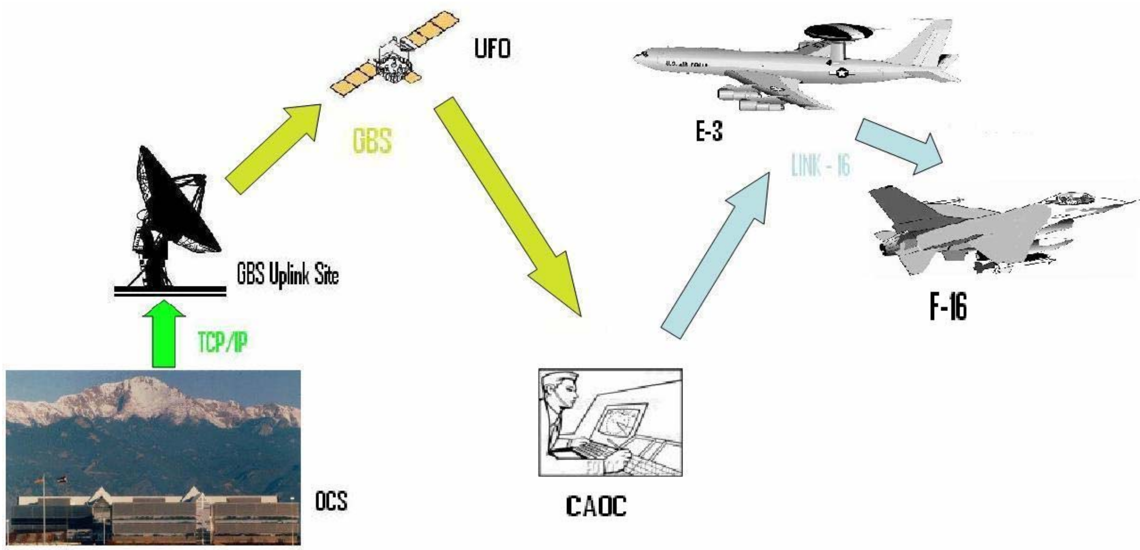

Figure 7. Air Force Architecture for GPS Ephemeris Message

B. GPS EPHEMERIS MESSAGE

The GPS ephemeris update message is generated by OMNIS, a software program, at the GPS Master Control Station, Schriever AFB, Colorado Springs, Colorado. The updates are generated every 15 minutes (Evans, 2005). The Naval Surface Warfare Center, Dahlgren Division (NSWC-DD) is currently working on the development of EPOCHA (Estimation of Precise Orbits and Clocks to High Accuracy), the next

generation satellite correction system. The EPOCHA system will generate the updates at a faster rate with potentially greater accuracy (Evans, 2005).

The information for the GPS ephemeris update message is taken from Interface Control Document (ICD) GPS-153 and ICD GPS-200. The GPS ephemeris message "shall utilize a basic format of a 1500 bit long frame made up of five subframes, each subframe being 300 bits long," (ICD GPS-200, 1993). The first two subframes of the ephemeris message are used for coordination and control purposes and not essential to the message. The next three subframes contain the GPS satellite orbit and clock corrections as calculated by OMNIS. Each set of five subframes contain the corrected satellite orbits and satellite clocks for one GPS satellite. In order for the user to receive the updated satellite orbits and clocks for each operational GPS satellite this message must be sent a total of twenty-four times, once for each operational GPS satellite.

This chapter outlines the architecture that is simulated using the NETWARS simulation and modeling program as well as the message that is sent through this simulation. The reason for this thesis is to simulate the delivery of the GPS Ephemeris Message to end users. A number of different simulations are run using this architecture and message format.

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IV. GPS EPHEMERIS MESSAGE BASELINE ARCHITECTURE SIMULATION

A. BASELINE ARCHITECTURE

1. Baseline Architecture Construction

The baseline simulation architecture was constructed using NETWARS Version 2005-1. This section provides a brief overview of the steps required to create this architecture in NETWARS. It does not provide each step, but rather attempts to give the user a general idea of the NETWARS program as well as the specific architecture that was created. The architecture was built using the Scenario Builder Module in NETWARS. NETWARS employs a Task Assistant Module to aid the user in developing a scenario and provides the user with a number of different workflows that can be employed. The workflow that was employed was *Develop a Communications Plan with Equipment List Manager*.

Two key functional elements that NETWARS employs to develop an architecture are Organizations and OPFACs. An Organization is defined in NETWARS as, "a group of OPFACs that can represent a military organization of physical location."[31] The organizations that were represented in the proposed architecture were the GPS MCS, GBS Continental Uplink Site, CVN/CAOC, E-2C/AWACS and the Tactical Aircraft. An OPFAC is defined in NETWARS as, "the fundamental building blocks of NETWARS. OPFACs contain communication device models and represent the communication assets for objects such as facilities, vehicles, airplanes, etc."[32] The OPFACS in the proposed architecture and their corresponding Organizations are:

1. NIPRNET IP Network: GPS MCS
2. NIPRNET IP Network: GBS Continental Uplink Site
3. GBS PIP: GBS Continental Uplink Site
4. GBS UFO: GBS Continental Uplink Site
5. GBS Receiver Suite: CVN/CAOC
6. JTIDS Class 2H Terminal: CVN/CAOC
7. JTIDS Class 2H Terminal: E-2C/AWACS
8. JTIDS Class 2M Terminal: Tactical Aircraft

[31] NETWARS Software Version 2005-1.

[32] NETWARS Software Version 2005-1.

After creating the Organizations and OPFACS the next step in NETWARS is to create connectivity links between the OPFACs to allow for the transfer of information. Different types of connectivity links are available depending upon the communications devices that are used.

The next steps in developing the architecture involved reviewing the requirements matrix, managing C4 equipment and defining the device application profiles. After this NETWARS allows the user to analyze the communications plan using the capacity planning features. This is done by adding demands, or traffic loads, to the architecture or converting application profiles into demands. At this point in the architecture development background utilization could be defined but it was not since the background utilization was zero for the baseline architecture.

Once the Organizations, OPFACs, connectivity links and demands were added to the Scenario Builder the network could be evaluated. Evaluating the network involves defining a number of time steps, length of time steps, and start and stop time for the scenario. Once the scenario is run, NETWARS produces a Capacity Planning Report. The Capacity Planning Report provides the user with an Executive Summary, Overall Peak Results, and Overall Average Results for each selected time interval. The Capacity Planning Report was used to analyze the compatibility and feasibility of the proposed architecture.

2. Time Intervals

Time intervals are extremely important to the operation of GPS Point Positioning. As discussed earlier, in a perfect scenario the updates of the satellite orbit errors and satellite clock errors would occur continuously in real time at the tactical aircraft so the time interval between updates would be zero. It is true that the corrections are not currently calculated in real time so this obviously would not occur in the near future. It is not unrealistic for us as planners to attempt to find the shortest possible time interval between data transfers even this time interval is less than the current processing output for the data by systems such as OMNIS. The development of EPOCHA will aid in faster processing of the orbit and clock corrections and therefore we will push the limits of consecutive ephemeris message transfers to the limits of the systems in this architecture.

The baseline simulation will be a time interval for the ephemeris message update architecture of fifteen minutes. Every fifteen minutes the ephemeris message is generated by OMNIS at Schriever AFB and sent through the architecture to the tactical aircraft. The purpose of the baseline simulation is to check for compatibility between the different communications systems and feasibility in transferring that amount of data over the communications systems.

3. Traffic

Military communication systems are constructed to handle traffic for the entire United States DoD and in cases of coalition war efforts they may be handling traffic for coalition partners and allies as well. The amount of information collected by ISR (Intelligence, Surveillance and Reconnaissance) assets increases everyday and information represents the key to modern warfare. The ability to analyze this information and transfer it to the tactical user is of primary importance to the success of modern military operations. The GBS transfer rate of 23.5 Mbps (Megabits per second) can certainly handle the GPS ephemeris updates but it is important to find out how much of the pipe the GPS ephemeris update will take up. GBS is designed to support a higher number of users and information so the GPS ephemeris updates, although important for GPS Point Positioning, cannot take up too much of the bandwidth that is needed by the rest of the end users. This service is important, and accurately guiding weapons with decimeter level accuracy to enemy targets is an important technological advance but not one that should be taking up a large percentage of available bandwidth.

The baseline architecture for the ephemeris message updates will have no extra traffic on the communications system that the message is transferred through. NETWARS allows the user to find the amount of available bandwidth that the ephemeris message will use so the residual bandwidth can be used by other military traffic.

4. Size and Number of Ephemeris Messages

The size of the GPS update ephemeris message, as outlined in Section IIIB, will be five subframes of 300 bits each for a total frame size of 1500 bits. In the baseline simulation the entire frame for each of the 24 operational GPS satellite will be transmitted over the baseline architecture to ensure that the end user has the information required to perform GPS Point Positioning. Changes that could be made to this in future

simulations could include cutting the frame message to only the last three subframes of the ephemeris message since the first two subframes do not carry critical information. It is hypothesized that the back end of the user's GPS receiver could be provided with the last three subframes and still correctly read the information to perform GPS Point Positioning.[33]

B. SIMULATION I: BASELINE ARCHITECTURE RESULTS

The results of Simulation 1 are displayed in Table 3:

Name	Data Rate (kbps)	Average Total Forward Utilization(%)	Average Total Reverse Utilization(%)	Average Foward Data Utilization(%)	Average Reverse Data Utilization(%)
E2C/AWACS to Tactical Aircraft	28.80	0.14	0.00	0.14	0.00
CVN/CAOC to E2C/AWACS	28.80	0.14	0.00	0.14	0.00
GBS UFO to GBS Receiver Suite	23,500.00	0.00	0.00	0.00	0.00
GBS PIP to GBS UFO	23,500.00	0.00	0.00	0.00	0.00
NIPRNET to GBS Uplink	10,000.00	0.00	0.00	0.00	0.00
GPS MCS to GBS Uplink via NIPRNET	10,000.00	0.00	0.00	0.00	0.00

Table 3. Simulation I Results

33 Evans meeting, 2005.

This table is taken from the NETWARS Capacity Planning Report with the specific table being taken from the Overall Average Utilization Report. Under the ‘name’ column the connectivity link is described and the connectivity links are listed in reverse order from the tactical aircraft to the ephemeris message generation site at Schriever AFB. The average utilization percentages for the continental IP network and the GBS uplink and downlink sites is effectively zero since these pipes are so large and the GPS update message is so small especially when it is being generated once every 15 minutes. It is interesting to note that the Link 16 connectivity links have much lower overall data rates, as one would expect, in comparison to the continental and satellite links and therefore these could be problematic in future scenarios when the time interval is less or the amount of forward and reverse traffic is increased.

This simulation does prove that the GPS ephemeris message will reach the tactical user without overloading the communication systems. The communication systems are also compatible with each other in terms of transferring the message between formats such as a packet switched IP network to GBS broadcast network to Link 16 Time Division Multiple Access. The one compatibility transfer that NETWARS was unable to perform was between the GBS downlink and the Link 16 Host Processor at the CVN node (CAOC node in the USAF). NETWARS was unable to construct a link between these two types of communication devices the research required to investigate the specifics of such transfer in the real world was beyond the scope of this thesis although future research could provide for an answer to this important question.

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V. GPS EPHEMERIS MESSAGE ARCHITECTURE SIMULATION WITH SHORTER TIME INTERVALS

The shorter time intervals for the broadcast of each ephemeris message from Schriever AFB to the tactical aircraft were proposed by Alan Evans, *Naval Surface Warfare Center*, *Dahlgren Division.* They were 2 minutes, 30 seconds, 6 seconds and 1 second. Each time interval was individually employed in a NETWARS simulation of the baseline architecture. In each simulation, at least five continuous time intervals of the ephemeris message broadcast were run so that overloads in the system were exacerbated throughout the architecture. The other factors considered in the baseline architecture remained the same:

1. Level of traffic set to zero on all connectivity links

2. Size of the individual correction message for each satellite included all five subframes for a total of 1500 bits.

3. Number of individual correction messages contained in the entire ephemeris message was 24, one for each operational GPS satellite.

A. SIMULATION II: 2 MINUTE TIME INTERVALS

The results of Simulation II are displayed in Table 4:

Name	Data Rate (kbps)	Average Total Forward Utilization(%)	Average Total Reverse Utilization(%)	Average Foward Data Utilization(%)	Average Reverse Data Utilization(%)
E2C/AWACS to Tactical Aircraft	28.80	1.04	0.00	1.04	0.00
CVN/CAOC to E2C/AWACS	28.80	1.04	0.00	1.04	0.00
GBS UFO to GBS Receiver Suite	23,500.00	0.00	0.00	0.00	0.00
GBS PIP to GBS UFO	23,500.00	0.00	0.00	0.00	0.00
NIPRNET to GBS Uplink	10,000.00	0.00	0.00	0.00	0.00
GPS MCS to GBS Uplink via NIPRNET	10,000.00	0.00	0.00	0.00	0.00

Table 4. Simulation II Results

B. SIMULATION III: 30 SECOND TIME INTERVALS

The results of Simulation III are displayed in Table 5:

Name	Data Rate (kbps)	Average Total Forward Utilization(%)	Average Total Reverse Utilization(%)	Average Foward Data Utilization(%)	Average Reverse Data Utilization(%)
E2C/AWACS to Tactical Aircraft	28.80	4.17	0.00	4.17	0.00
CVN/CAOC to E2C/AWACS	28.80	4.17	0.00	4.17	0.00
GBS UFO to GBS Receiver Suite	23,500.00	0.00	0.00	0.00	0.00
GBS PIP to GBS UFO	23,500.00	0.00	0.00	0.00	0.00
NIPRNET to GBS Uplink	10,000.00	0.01	0.00	0.01	0.00
GPS MCS to GBS Uplink via NIPRNET	10,000.00	0.01	0.00	0.01	0.00

Table 5. Simulation III Results

C. SIMULATION IV: 6 SECOND TIME INTERVALS

The results of Simulation IV are displayed in Table 6:

Name	Data Rate (kbps)	Average Total Forward Utilization(%)	Average Total Reverse Utilization(%)	Average Foward Data Utilization(%)	Average Reverse Data Utilization(%)
E2C/AWACS to Tactical Aircraft	28.80	20.83	0.00	20.83	0.00
CVN/CAOC to E2C/AWACS	28.80	20.83	0.00	20.83	0.00
GBS UFO to GBS Receiver Suite	23,500.00	0.03	0.00	0.03	0.00
GBS PIP to GBS UFO	23,500.00	0.03	0.00	0.03	0.00
NIPRNET to GBS Uplink	10,000.00	0.06	0.00	0.06	0.00
GPS MCS to GBS Uplink via NIPRNET	10,000.00	0.06	0.00	0.06	0.00

Table 6. Simulation IV Results

D. SIMULATION V: 1 SECOND TIME INTERVALS

The results of Simulation V are displayed in Table 7:

Name	Data Rate (kbps)	Average Total Forward Utilization(%)	Average Total Reverse Utilization(%)	Average Foward Data Utilization(%)	Average Reverse Data Utilization(%)
E2C/AWACS to Tactical Aircraft	28.80	125.00	0.00	125.00	0.00
CVN/CAOC to E2C/AWACS	28.80	125.00	0.00	125.00	0.00
GBS UFO to GBS Receiver Suite	23,500.00	0.15	0.00	0.15	0.00
GBS PIP to GBS UFO	23,500.00	0.15	0.00	0.15	0.00
NIPRNET to GBS Uplink	10,000.00	0.36	0.00	0.36	0.00
GPS MCS to GBS Uplink via NIPRNET	10,000.00	0.36	0.00	0.36	0.00

Table 7. Simulation V Results

E. SUMMARY OF TIME INTERVAL SIMULATION RESULTS

The results of Simulations II, III, IV and V are addressed below. As the time interval between GPS Ephemeris Message updates decreases the Average Total Forward Utilization of the connectivity links increases. The amount of the increase in utilization is inversely proportional to the decrease in the time interval for all six connectivity links in the architecture. For example, in Simulation II the Average Total Forward Utilization for the E2/AWACS to Tactical Aircraft connectivity link was 1.04% with 2 minute time intervals. In Simulation III, the Average Total Forward Utilization of the same connectivity link increased to 4.17%, an increase by a factor of four, with 30 second time intervals between message updates. Thirty-second time intervals are a factor of four decrease from two minutes.

In Simulations II-V the terrestrial IP network and GBS connectivity links had a maximum Average Total Forward Utilization of .36% and .15%, respectively, in the 1 second time interval scenario (Simulation V). The authors conclude that the terrestrial IP network and GBS are effectively large enough to handle near-continuous GPS ephemeris message updates without significantly effecting their overall utilization. The terrestrial IP network and GBS will effectively deliver the ephemeris message to the CVN/CAOC node; the effective transfer of the message from this node is to the end user is the more challenging part of this simulation.

The following graph displays the Average Total Forward Utilization (%) of the E2/AWACS to Tactical Aircraft connectivity link versus time interval between ephemeris message updates in seconds:

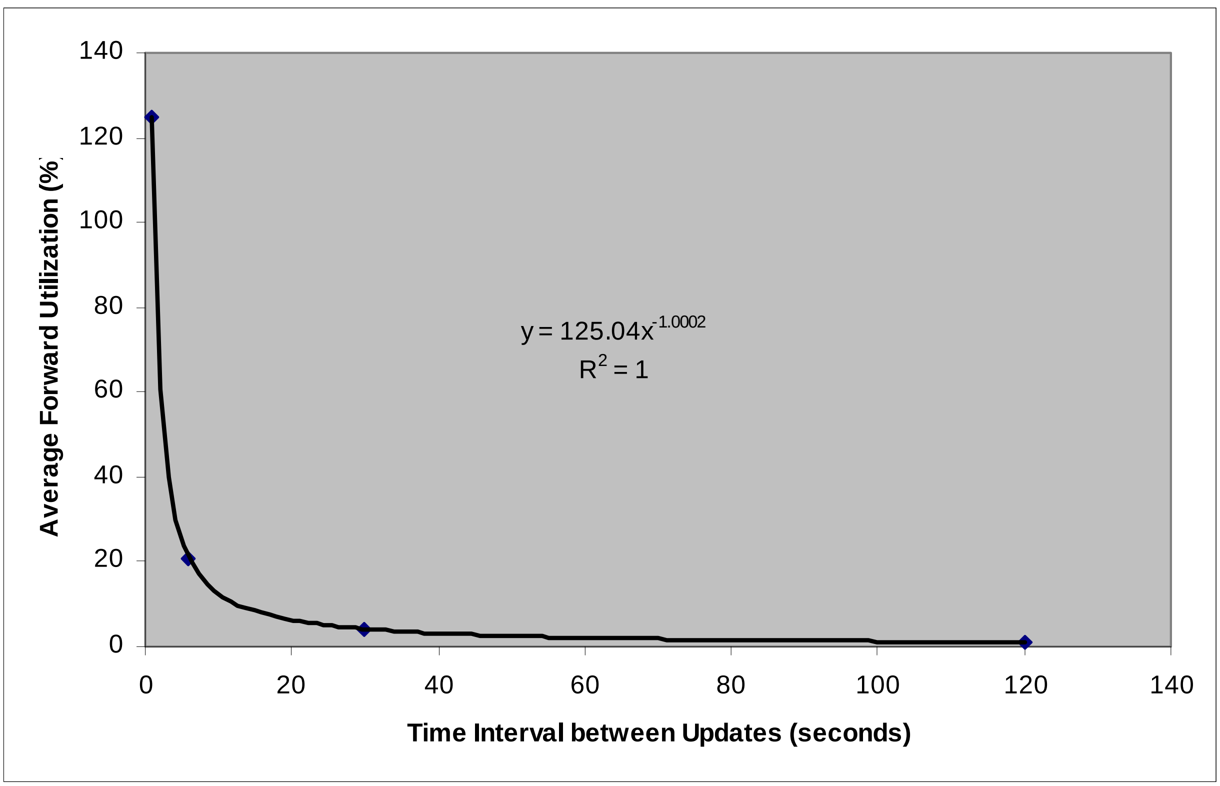

Figure 8. Average Forward Utilization (%) versus Time Interval between Ephemeris Message Updates (seconds) for the Link 16 connectivity Links

The graph and trend-line generated from the results of the four simulations allows for the calculation of the Average Forward Utilization percentage for any time interval.

It is also important to note that the 100% forward utilization occurs at a time interval of approximately 1.25 seconds. Therefore, the authors conclude that the minimum time interval that the Link 16 network can support without any other competing users or data on the network is 1.25 seconds. Ephemeris message that are sent with time intervals of less than 1.25 seconds will not reach the tactical user.

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VI. GPS EPHEMERIS MESSAGE ARCHITECTURE SIMULATION WITH BACKGROUND TRAFFIC

The addition of traffic to the terrestrial communication systems that are being used in these simulations is important to add to the real-world applicability of the simulation. As discussed in Section IV.A.3, there are many users on each of these systems who required bandwidth for their information. After reviewing the results from Simulations I-V, it was decided that the only connectivity links that would have traffic loads placed upon them in addition to the ephemeris message would be the *Link 16 Host to Airborne Relay* link and the *Airborne Relay to Tactical Aircraft* link. The reasons for this decision are twofold. First, the GBS and IP network links have large enough data throughputs that no matter how often the GPS Ephemeris Message is sent it should not overload these networks. The addition of background traffic to these links will not affect the deliverability of the GPS Ephemeris Message. Second, the compatibility between these two networks in terms of transferring the message seamlessly between was confirmed by NETWARS in Simulations I-V.

There were three different simulations run with the amount of traffic varying in each simulation on Link 16 connectivity links. The percentage of data traffic represents the percentage of forward and reverse link utilization. The three simulations were:

V. 0% data traffic with 1 Voice Channel

VI. 50% data traffic with 0 Voice Channels

VII. 50% data traffic with 1 Voice Channel

The time intervals for these simulations will be 10 seconds between each GPS Ephemeris Message broadcast. This time interval was chosen because it produced a reasonable amount of forward utilization in the connectivity links but it did not overload them. It provides a balance between updating in real time while not overloading the Link 16 Tactical Data network.

The implementation of data traffic and a single voice channel in Simulation VII, is to represent a mission such as a tactical air strike that would use GPS Point

Positioning. Gonzalez et al develop an air-air combat scenario with an AWACS and four tactical aircraft (F-15s) using a Link 16 network with one voice channel and data exchange. Although their scenario is a different mission from one that would be applicable to GPS Point Positioning, the number of aircraft is the approximately the same for a tactical air strike. The use of a 50% data traffic load is proposed by the authors but Stinson defined data loading in a Link 16 network as 30% for lightly loaded, 60% for moderately loaded and 90% for heavily loaded. In context, it is important to note that a 50% data traffic load is slightly less than a moderate load for the Link 16 so we feel this is a reasonable assumption on average for most Link 16 operations involving tactical air strikes.

A. SIMULATION VI: 10 SECOND TIME INTERVALS WITH 1 VOICE CHANNEL

The results for Simulation VI are displayed in Tables 8:

Name	Data Rate (kbps)	Average Total Forward Utilization (%)	Average Total Reverse Utilization (%)	Average Forward Data Utilization (%)	Average Reverse Data Utilization (%)	Average Voice Utilization (%)
E2C/AWACS to Tactical Aircraft	28.80	40.27	27.78	12.50	0.00	50.00
CVN/CAOC to E2C/AWACS	28.80	40.27	27.78	12.50	0.00	50.00

Table 8. Simulation VI Results

The results for Simulation VI show that the GPS Ephemeris Message was received by the tactical aircraft successfully with one voice channel. The Link 16 Tactical Data Network was able to handle the ephemeris message and the voice channel.

The Average Voice Utilization (%) is 50% for one Voice Channel because Link 16 can support two Voice Channels so one voice channel represents 50% of the Voice Utilization.

B. SIMULATION VII: 10 SECOND TIME INTERVALS WITH 50% DATA TRAFFIC

The results for Simulation VII are displayed in Tables 9:

Name	Data Rate (kbps)	Average Total Forward Utilization (%)	Average Total Reverse Utilization (%)	Average Forward Data Utilization (%)	Average Reverse Data Utilization (%)	Average Voice Utilization (%)
E2C/AWACS to Tactical Aircraft	28.80	62.50	50.00	62.50	50.00	0.00
CVN/CAOC to E2C/AWACS	28.80	62.50	50.00	62.50	50.00	0.00

Table 9. Simulation VII Results

The results for Simulation VII show that the GPS Ephemeris Message was received by the tactical aircraft successfully with 50% data traffic. The Link 16 Tactical Data Network was able to handle the ephemeris message in addition to the 50% data traffic.

C. SIMULATION VIII: 10 SECOND TIME INTERVALS WITH 50% DATA TRAFFIC AND 1 VOICE CHANNEL

The results for Simulation VIII are displayed in Table 10:

Name	Data Rate (kbps)	Average Total Forward Utilization (%)	Average Total Reverse Utilization (%)	Average Forward Data Utilization (%)	Average Reverse Data Utilization (%)	Average Voice Utilization (%)
E2C/AWACS to Tactical Aircraft	28.80	90.28	77.78	62.50	50.00	50.00
CVN/CAOC to E2C/AWACS	28.80	90.28	77.78	62.50	50.00	50.00

Table 10. Simulation VIII Results

The results for Simulation VIII show that the GPS Ephemeris Message was received by the tactical aircraft over Link 16 but the average total forward utilization of both links was over 90%. This result is problematic because if any more data is placed on the network or another voice channel is required the network will be overloaded and messages will not be deliverable.

Additionally, it is important to note that the 50% residual traffic data load assumed by the authors could certainly increase depending upon the specific operation. As mentioned above, a moderately loaded Link 16 network has traffic of 60% so the 50% assumption in this thesis could increase in some scenarios. Applying a moderately loaded Link 16 network to Simulation VIII results in the Average Total Forward Utilization of the network being above 100%.

VII. GPS EPHEMERIS MESSAGE ARCHITECTURE SIMULATION VARYING THE NUMBER AND SIZE OF THE EPHEMERIS MESSAGES

The final variation to the GPS Ephemeris Message broadcast is to vary the number and size of the individual ephemeris messages. The number of individual ephemeris messages contained in the broadcast for the baseline architecture was twenty-four, one for each GPS satellite. A change that could be made to the message format would be to transmit a smaller number of frames to only correct the satellite orbit and satellite clocks for those specific satellites that the GPS receiver is actually utilizing. This architecture is difficult to realize because it would require prior coordination between the GPS receiver onboard the tactical aircraft and the GPS MCS because the MCS would need to know which satellites were in the aircraft's AOR (Area of Operations) so it would know which updates to send to it .

This thesis considered the idea of sending the entire set of 24 individual GPS ephemeris messages over the IP network and GBS to the CVN/CAOC node. At the CVN/CAOC node, the flight plan for each specific tactical aircraft is known due to the presence of the ATO (Air Tasking Orders). A software program at the CVN/CAOC node reduces the size of each entire GPS ephemeris message to include only those updates that correspond to GPS satellites that will be persistent above tactical aircraft's AOR (Area of Operations). These smaller messages could then be sent out of Link 16 Tactical Data Network using the E-2C or AWACS as an airborne relay to the tactical aircraft. For this system to work the software program would need to know precise orbits for all GPS satellites over the next 24 hour period and be able to match these orbits with the flight plans for the aircraft. The potential advantages of such a system would be that less data would need to be transferred over Link 16 to the tactical aircraft; tactical aircraft GPS receivers would not be receiving satellite orbit and satellite clock updates for satellites that were not in view. The potential disadvantages of such a system would be that it would require extensive coordination between the ATO, GPS satellite orbits and individual aircraft to ensure that each aircraft was receiving the correct corrections. Additionally, the size of the ephemeris messages is relatively small so the overall link

utilization gain realized from transferring only 50% of them does not seem to compensate for the increased complexity in this architecture. The lack of a feasible gain in total link utilization from reducing the number of ephemeris messages broadcast to each individual aircraft means that this idea was not simulated using NETWARS.

Reducing the size of the individual ephemeris messages from five subframes to three subframes is a second way to reduce the size of the entire ephemeris message. The first two subframes contain non-critical information but it is not known if the GPS receiver will accept the last three subframes without the first two in the ICD-GPS 200 format. The advantage of reducing the individual ephemeris message by two subframes, which would decrease the overall message size by 40%, is less total utilization of the Link 16 tactical data network. The disadvantage of reducing the message size is that it may not be compatible with the GPS receiver. The advantages to this message size reduction outweigh the disadvantage of possible compatibility problems because less utilization of the Link 16 is important to this simulation; it allows for shorter time intervals between updates as well as increased traffic by other users with overloading the network. If the message is not compatible then the updates can revert to the five-subframe format, but simulating three subframes is a useful endeavor for planning purposes. The reduced GPS Ephemeris message, containing only three subframes per individual satellite update (24 satellites total) is simulated in Simulation IX. The other parameters of Simulation IX remain the same as Simulation VIII: 10 second time intervals between updates, 50% background data traffic and 1 voice channel in use. The results for Simulation IX are listed in Table 11:

Name	Data Rate (kbps)	Average Total Forward Utilization (%)	Average Total Reverse Utilization (%)	Average Forward Data Utilization (%)	Average Reverse Data Utilization (%)	Average Voice Utilization (%)
E2C/AWACS to Tactical Aircraft	28.80	86.11	73.61	58.33	50.00	50.00
CVN/CAOC to E2C/AWACS	28.80	86.11	73.61	58.33	50.00	50.00

Table 11. Simulation IX Results

The Simulation IX results are similar to those found in Simulation VIII except that the Average Total Forward Utilization and Average Total Data Utilization percentages are slightly less due to the reduction in size of the ephemeris message. Despite this reduction, the overall utilization is near 100% as indicated by the red outlines, and the Link 16 network is in danger of being overloaded if more information peaks at any given time period.

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VIII. CONCLUSION

This thesis simulated the broadcast of a GPS Ephemeris message over terrestrial communication systems to end users using the NETWARS modeling and simulation tool. The GPS Ephemeris message contains satellite and clock updates for the GPS receiver to allow for more accurate target geolocation through GPS Point Positioning. GPS Point Positioning provides real-time, kinematic, decimeter level accuracy to the user which means greater weapon effectiveness and the potential to reduce collateral damage for the warfighter.

The NETWARS simulation was successful in broadcasting the GPS Ephemeris message to tactical aircraft users in flight. The specific attributes of the ephemeris message that were investigated in the simulation were time intervals, residual traffic, message size, and compatibility between systems. Time intervals addressed how often the GPS Ephemeris message could be sent from the origination point at the MCS to the tactical user without overloading the system. Residual traffic addressed how much residual traffic could conceivably be present on the systems while still allowing the ephemeris message to reach the tactical user. Size of the message investigated the feasibility of reducing the ephemeris message size in two different ways and how a size reduction affected the overall performance of the communication systems. The trade-offs between the size reduction against less network utilizations were analyzed. Finally, the compatibility between the IP network, GBS, and Link 16 were addressed.

The results of the time interval simulations (Simulations I, II, III, IV and V) showed that the IP network and GBS could support almost continuous ephemeris message updates because of their large data rates. The Link 16 tactical data network was able to support time intervals of 15 minutes, 2 minutes, 30 seconds and 6 seconds adequately while still providing throughput to other ‘probable’ users. Link 16 was overloaded when the time interval was set to 1 second and ephemeris messages then dropped from the broadcast. The authors conclude that without residual traffic on the network, which is a fairly unreasonable assumption, the optimum time interval would be

approximately 6 seconds. Additionally, it was concluded that if residual traffic was assumed to be present on the network then the time intervals should not be less than 10 seconds.

The results of the residual traffic simulation built upon the time interval simulation results. The residual traffic simulations (VI, VII and VIII) introduced voice traffic, data traffic, and voice and data traffic to the architecture, respectively. The results of these simulations seemed to validate the conclusion that the ten second time interval for the GPS updates with traffic was close to the minimum time interval. The only possible problems occurred in Simulation VIII, which was close to overloading the network with too much data and voice traffic. The conclusion from these results is that in low-tempo operations without a large volume of messages or voice traffic ten second time intervals are still feasible. In higher-tempo operations involving multiple aircraft on the same Link 16 network flying various missions, especially operations utilizing both available voice channels, a longer time interval of thirty second ephemeris updates is the maximum frequency recommended.

Reducing the size of the ephemeris message was addressed in two different ways. The first reduction involved broadcasting only those individual ephemeris messages that correspond with satellites in the tactical aircraft field of view. It was predicted that this would reduce the ephemeris message size by approximately 50 percent, but the concept was not feasible for simulation. The disadvantages of this reduction would be that it would require extensive coordination between the ATO, GPS satellite orbits, and individual aircraft to ensure that each aircraft was receiving the correct set of corrections corresponding to the GPS signals it was receiving.

The second reduction of the ephemeris message involved removing the first two subframes from each individual satellite’s update and only broadcasting the last three subframes containing the orbit and clock updates. The feasibility of this size reduction was greater than the previous one; the only drawback was that the ephemeris message may be unreadable at the GPS receiver. Simulation IX was run incorporating the results of the time interval and residual traffic simulations and the results showed that the 40% size reduction in the ephemeris message was marginally effective in reducing Link 16

utilization. The conclusion from this simulation was that reducing the message size by subtracting the extra subframes could prove very useful in the future and would allow for faster time intervals. In terms of the present, this thesis' overall recommendation for the GPS message updates is to transmit the entire message over the proposed architecture using a maximum of ten second time intervals. Although the system demonstrated that it could support ten second intervals, it is interesting to note that OMNIS currently produces satellite and orbit clock corrections every 15 minutes.

The compatibility between the terrestrial communications systems was addressed in this thesis to some extent for the proposed architecture. The NETWARS simulations demonstrated that the IP network and GBS were compatible and the ephemeris message moved seamlessly between them. The two nodes that were assumed to be compatible but were not simulated in this thesis were the CVN/CAOC node and the tactical aircraft node. The transfer of the ephemeris message from the GBS downlink onboard the CVN/CAOC to the Link 16 Tactical Data Network could not be simulated using NETWARS, so the compatibility between these two networks could not be confirmed. The second node that was assumed to be compatible but was unproven in the simulation was the transfer of the ephemeris message from the JTIDS Terminal (Class II) and the GPS receiver aboard the tactical aircraft. Future work could involve testing these two nodes for compatibility in the tactical environment.

The simulation of the GPS broadcast ephemeris message was successful given the proposed architecture with constraints of ten second time intervals, 50% residual traffic, one voice channel and no message size reduction.

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APPENDIX

The following Appendix outlines the basic procedure for obtaining NETWARS and running the simulations described in this thesis. The process outlined below does not include every single step taken in the development of the architecture and the running of the simulations found in this thesis; rather it gives an overview of specific procedures that were used and when repeated will allow the programmer to develop the entire architecture and run the simulations described in this thesis. Simulation VII is specifically outlined in this appendix.

1. Obtain and Install ETWARS Version 2005-1

    a. Contact Karen Chin at NETWARS Program Office

        EMAIL: chin_karen@bah.com

        WEBSITE: http://www.disa.mil/main/prodsol/netwars/

    b. Fill out Justification Form

    c. Copy of NETWAR will be sent via FedEx

    d. Install NETWARS

    e. Register License using the License Manager (this can be done via email)

2. Obtain Link 16 SPAWAR Contributed Model

    a. Raise the directory C:\Netwars\Sim_Domain\op_models\contributed_models\navy_spawar_models to the top list (Edit->Preferences->Advanced->mod_dirs, select Move Up)

    b. Uncomment the first section NAVY contributed links in the LinkTypeMap.gdf file under C:\Netwars\Scenario_Builder\10.5.A\netwars\rules

    c. Update the repository to include these new models (Edit->Preferences->Advanced and set Repositories to empty.

3. Configure Object Palettes

    a. Click the **Configure Palette** button located at the upper-right corner of the object palette to open the Configure Palette dialog box.

    b. Click the **Node Models** button to add specific models from the palette.

    c. Toggle the Status column to **included** for the Link_16_Host_Processor

d. Click **OK**, specify **GPS** in the Save As dialog box, and click in **OK** again to complete.

e. Repeat procedure to Configure Object palette for JTDS Terminal.

4. Construct Architecture of Organizations, OPFACS and Connectivity Links in the Scenario Builder using the NETWARS – Task Assistant

a. Click the **Object Palette** button located along the Taskbar

b. Click the dropdown menu and choose **Custom_Organizations**

c. Click and drag the **New_Org** to the Scenario Builder map

d. Right click on the **New_Org** and choose **Edit Netwars Attributes** and rename it to **CVN**.

e. Click the **Object Palette** button located along the Taskbar

f. Click the dropdown menu and choose **GPS** (this menu is specific to where the OPFACS were saved on the Object Palette in 3.d)

g. Click and drag the **Link_16_Host_Processor** to **CVN** on the Scenario Builder map.

h. Repeat this procedure for all organizations and OPFACS in the architecture (Section IV.A.1)

i. Click the **Show Treeview** button located along the Taskbar

j. Click the **Define Infrastructure** button located in the lower-left corner of the Define Scenario dialog box.

k. Click the dropdown menu **Relationships** in the upper-right corner of the Define Infrastructure dialog box and change it to **Links.**

l. Check the E-2C Hawkeye_JTIDS Terminal and the Tactical Aircraft_JTIDS Terminals in the left hand column and click the **Define** button located in the middle-bottom area of the Define Infrastructure dialog box.

m. Right click on the **JTIDS Terminal to JTIDS Terminal** link listed in the right column of the Define Infrastructure dialog box. Set the *Name*: E-2C to Tactical Aircraft. Click **Ok.**

5. Run Simulation VII

a. Open Traffic->Specify Demands

b. From the Producer Tree check E-2C Hawkeye_JTIDS Terminal

c. From the Consumer Tree check Tactical Aircraft_JTIDS Terminal

d. Click **Create Demand** button located at the bottom of the Specify Demand dialog box.

e. Set *Traffic Type*: Data, *Size:* 4500 (bytes), *Average:* 10 (seconds), *Distribution Type:* CONSTANT, *Priority*: ROUTINE, *Classification*: Link 16_NPG_08_Weapons_Coordination, *Producer Device*: E-2C Hawkeye_JTDS Terminal, *Consumer Device*: Tactical Aircraft_JTIDS Terminal, *Equipment Type*: JTIDS, and *Perishability*: 10 (seconds). Click **Ok**.

f. Repeat procedure to Specify Demand for CVN_Link 16 Host Processor to E-2C Hawkeye_JTIDS Terminal connectivity link.

g. Open Capacity Planning->Evaluate

h. Set *Number of Time Steps*: 5 (seconds), *Length of Time Steps*: 10 (seconds), *Start Time*: 0 hours, 0 minutes, 0 seconds. Click **Run**.

i. The Results of the Simulation are displayed in the Capacity Planning Report.

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LIST OF REFERENCES

Alspaugh, Chris, Dr. Nikhil Dave, Tom Hepner, Andy Leidy, Dr. Mark Stell, Dr. Cam Tran, Heather Woods, Wonita Youm and Dr. Albert K. Legaspi. "Modeling and Simulation in Support of Network Centric Warfare Analysis." 2004 Command and Control Research and Technology Symposioum: 15-17 June 2004.

Bisnath, S., Jannasch, B., Langley, R. B., Peeters, B., *THE GPS BROADCAST ORBITS: AN ACCURACY ANALYSIS*, University of New Brunswick, 16-23 July, 2000. 33rd COSPAR Scientific Assembly, Warsaw. [http://gauss.gge.unb.ca/papers.pdf/COSPAR2000.pdf] July 20, 2005.

Colombo, O. L., et al., "Evaluation of Real-Time, Long-Range, Precise, Differential, Kinematic GPS Using Broadcast Orbits," Proc. ION GPS/GNSS 2003, Portland, OR, Sept. 2003.

Cox, Criston W., "Optimizing Bandwidth in Tactical Communications Systems," Masters Thesis, Naval Postgraduate School, Monterey, CA, June 2005.

Cunningham, James P. et al, "Rapid and Accurate Target Geolocation Using Visible-Light and IR Cameras on an Unmanned Aerial Vehicle," *National Fire Control Symposium,* Kauai, Hawaii, August 2004.

Davidson, Joe, *Air Force Space Command Continues GPS Modernization,* Space Daily, August 22, 2005. Available: [www.spacedaily.com/news/gps-05zzzt.html], September 26, 2006.

Evans, A.G., et al., "Fusion of Reference-Aided GPS, Imagery and Inertial Information for Airborne Geolocation," Proc. ION GPS-2000, Salt Lake City, UT, Sept. 2000.

Evans, A.G. (ed.) et al., "The Global Positioning System Geodesy Odyssey," NAVIGATION: Journal of the Institute of Navigation, Vol. 49, No.1, Spring 2002, pp. 7 - 33.

Evans, Alan G., Meeting, Naval Postgraduate School, June 29, 2005.

Gonzalez, Daniel, John Hollywood, Gina Kingston and David Signori, "Network-Centric Operations Case Study," National Defense Research Institute, RAND Corporation, 2005.

Hatch, Ron et al., "Starfire: A Global High Accuracy Differential GPS System," Paper 1.6.

Hermann, B.R. and Malys, S., "Precise Absolute Navigation: An Evaluation of PPS Position Improvement," Institute of Navigation, ION-GPS-95, Palm Springs, CA, September 1995.

Hofmann-Wellenhof, Bernhard, *GPS Theory and Practice*, 5th ed., Springer-Verlag Wien, New York, 2001.

Kaplan, Elliot D., *Understanding GPS: Principles and Applications*, Artech House Publishers, 1996.

Muellerschoen, Ronald J. et al, “Results of an Internet-Based Dual-Frequency Global Differential GPS System,” *Jet Propulsion Laboratory, California Institute of Technology.*

Norton, Elaine, “JTIDS DMSMS Program,” 1999 DMSMS Conference: April 22, 1999.

Racoosin, Charles, “Lesson 22A GPS Update,” Naval Postgraduate School SS3011, Spring 2005.

Stinson, Clinton W. “Internet Protocol (IP) over Link 16,” Air Force Institute of Technology, March 2003.

Vincent, Drew, “Talon NAMATH Briefing,” Air Force TENCAP, April 21, 2005.

Weinzettle, John, “Combined Test Bed (CTB) Distributed Engineering Plant (DEP),” SPAWAR Systems Center San Diego.

Wheeler, Willliam L., “Worldwide Meteorological and Oceanographic Distribution using the Global Broadcast Service,” *Naval Postgraduate School Thesis*, June 2001.

Zumberge, J.F.; Heflin, M.B.; Jefferson, D.C; Watkins, M.M.; and Webb, F.H., “Precise Point Positioning for the Efficient and Robust Analysis of GPS Data From Large Networks,” Journal of Geophysical Research, Vol. 102, No. B3, pp. 5005–5017, March 10, 1997.

Boeing, *UHF Follow-On Global Broadcast Service* not dated.
[http://www.boeing.com/defense-space/space/bss/factsheets/601/gbs/gbs.html] July 12, 2005.

DISA: Department of Defense, *NETWARS (Network Warfare Simulation)* not dated.
[http://www.disa.mil/main/prodsol/netwars/index/html] August 30, 2005.

FAA, *GPS Basics* not dated.
[http://www.faa.gov/gpsbasics/GPSmodernization-text.htm] June 15, 2005.

FAS, *Global Broadcast Service* not dated.
[http://www.fas.org/spp/military/program/com/gbs.htm] July 12, 2005.

FAS, *Joint Tactical Information Distribution System* not dated.
[http://www.fas.org/man/dod-101/sys/land/jtids.htm] June 30, 2005.

Garmin International Inc., *What is GPS?* not dated.
[http://www.garmin.com/aboutGPS/] July 9, 2005.

Global Security.org, *Joint Tactical Information Distribution Systems* not dated
[http://www.globalsecurity.org/military/systems/ground/jtids.htm] June 30, 2005.

Global Security.org, *GPS III/ GPS Block III* not dated
[http://www.globalsecurity.org/space/systems/gps_3.htm] September 26, 2005.

GPS User Equipment Interface Control Document for the GPS Standard Serial Interface Protocol of DoD Standard GPS UE Radio Receiver, ICD-GPS-153, December 10, 2002.

Headquarters United States Pacific Command, *United States Pacific Command Global Broadcast Service Concept of Operations,* 3 December 1998.

Interface Control Document, No. ICD-GPS-200, pp. 59-62, June 19, 1993.

Jane's Online, *Digital Datalinks* January 17, 2005.
[http://online.janes.com/] June 30, 2005.

Jane's Online, *TADIL-J* not dated
[http://online.janes.com/] July 12, 2005.

MILSATCOM, *Global Broadcast Service Point Program* not dated.
[http://www.losangeles.af.mil/SMC/MC/gbs.htm] July 12, 2005.

NETWARS Version 2005-1 Software.

Raytheon, *Global Broadcast Service Enhanced Internet Protocol (IP) architecture* not dated. [http://www.raytheon.com/products/gbs/] July 12, 2005.

"TADIL J: Introduction to Tactical Digital Information Link J and Quick Reference Guide." FM 6-24.8, MCWP 3-25C, NWP 6-02.5, AFTTP(I) 3-2.27. Air Land Sea Application Center: June 2000. Available ONLINE: General Dennis J. Reimer Training and Doctrine Digital Library at [www.adtdl.army.mil]. June 30, 2005.

Trimble, *All About GPS* not dated.
[http://www.trimble.com/gps/index.html] July 9, 2005.

United States Navy Fact File, *F/A-18 Hornet* last updated March 21, 2004.
[http://www.chinfo.navy.mil/navypalib/factfile/aircraft/air-fa18.html] August 30, 2005.

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